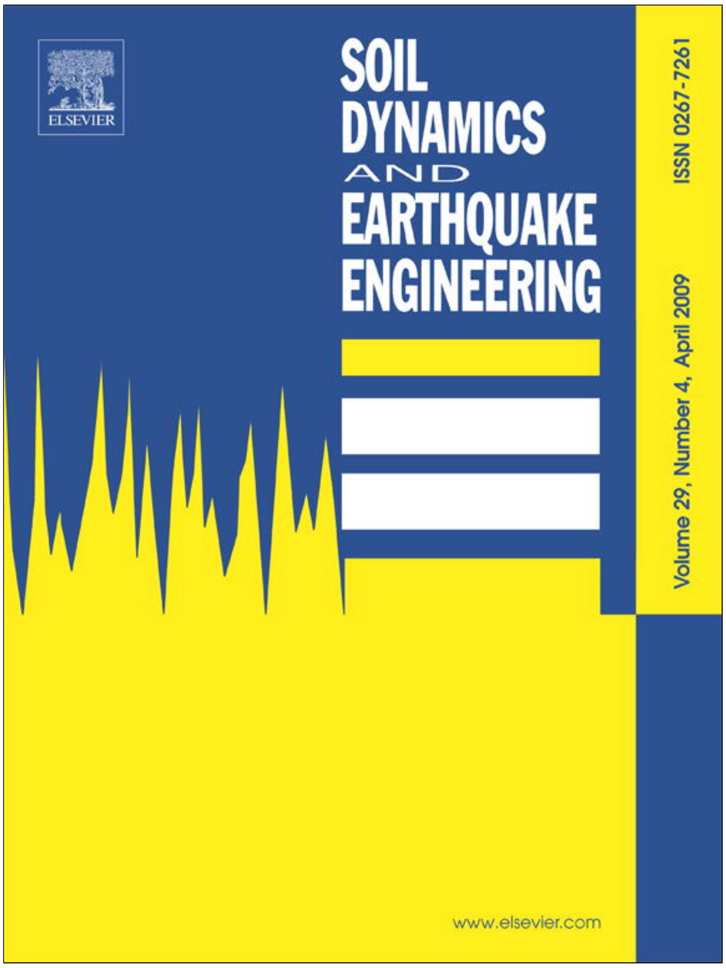
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A new definition of strong motion duration and related parameters affecting the response of medium–long period structures

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ABSTRACT

This study presents a new definition of the strong motion duration combining the alternative bracketed and significant duration definitions. Based on the time integral of the absolute ground velocity, a new index is defined, as cumulative absolute displacement (CAD), and used to estimate the strong motion duration. The proposed bracketed-significant duration t_{bs} is found to be well correlated with the strong motion part of the records, especially in the case of near-source events. The duration t_{bs} and the CAD index are used to assess the anticipated structural behavior of medium–long period structures.

Two normalized parameters P_1 and P_2, representing the amplification of structural response and the number of equivalent loading cycles, respectively, are determined in terms of the t_{bs} and CAD and the spectral velocity associated with the medium–long period range. P_1 and P_2 appear to be better correlated with the structural response than established well-known indices.

1. Introduction

Earthquake strong ground motion is a complex natural phenomenon associated with the abrupt energy release caused by fault rupture. The intensity of the event has been described in terms of the perceived effects of ground motion according to different intensity scales. The availability of strong ground motion records permits use of more consistent, quantitative indices of strong motion severity, taking into account the amplitude, duration and frequency content of the records [1–3].

The most frequently used intensity parameters are the maximum ground acceleration and velocity, the significant duration of the strong motion and the spectral amplitudes for different characteristic periods of the strong motion records [1–3]. In his pioneering work, Housner [4] proposed that, in order to define an adequate severity index, the simultaneous use of at least two parameters is needed. He suggested that the selected parameters should be related to the duration and the average rate of energy release of the most intense part of the strong ground motion. This portion of the record is associated with the interval of the Arias integral presenting the steepest gradient. The average gradient, defined as the 'power' of the earthquake motion, and the duration of this interval are associated with the duration and average rate of intense energy release and the severity of the seismic hazard at the recording site.

Trifunac has defined as the significant duration of the strong ground motion the time interval between 5% and 95% of the Arias intensity [5]. However, there is still not a consensus on the definition of the significant duration of strong ground motion. A similar definition by Pereira and Bommer [6] proposes, as effective duration, the time interval between two particular thresholds of the Arias intensity. Alternative definitions of bracketed duration, based on the time interval between the first and last acceleration excursions greater than an absolute or relative threshold of the acceleration time history, have also been presented [7,8].

Different indices have been proposed in order to correlate ground motion parameters, directly estimated from the strong motion time histories, with structural response and subsequent damage. Amongst the most commonly used ground motion indices are:

(i) The mean-square, root-square and root-mean-square values of the square acceleration, velocity and displacement integrals that are associated with the energy release of the ground motion [9],
(ii) The incremental velocity (IV) and incremental displacement (ID) calculated by integrating the individual pulses in the acceleration and velocity time histories, respectively [10],
(iii) The cumulative absolute velocity (CAV), that is, the integral of the absolute acceleration over the ground motion duration [11],
(iv) The characteristic intensity (CI) proposed by Ang [12]

$$\mathrm{CI} = a_{\mathrm{rms}}^{1.5} t_{\mathrm{d}}^{0.5} \tag{1}$$

where a_{rms} and t_{d} are the root-mean-square acceleration and the duration according to Trifunac [5], respectively,

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(v) The parameter proposed by Fajfar [13]

$$F_I = \max v_g t_d^{0.25} \quad (2)$$

where $\max v_g$ is the peak ground velocity.

The indices combine amplitude and duration of the ground motion time histories in order to account for earthquake intensity. Cabanas et al. [14] state that the estimation of structural response considering both amplitude and duration produces better results in what regards the damage potential of earthquakes. A comparative study of duration and energy characteristics and their correlation with intensity measures, valid for Greek records, has been presented by Koliopoulos et al. [15].

It must be noted that most intensity factors and related studies are based on far-field records. The increased density of accelerograph networks during the last decades has made available a large number of near-source records characterized by clear long period pulses, especially in the velocity and displacement time histories. Strong velocity pulses, a characteristic of forward directivity, are closely related to the severity of ground motion and its effects on medium and long period structures. The strong motion duration, expressed as a number of velocity cycles, is another parameter affecting the intensity of strong ground motion. The acceleration time history of near-source records is usually dominated by a more prominent high-frequency content that is related to the lower period spectral region [9,16]. Thus, there is a need to assess the effectiveness of established indices for near-source records. This issue is addressed in the following sections.

2. Definitions and description of methodology

2.1. New definition of duration

In this work, emphasis is placed on the medium and long period region of the velocity spectrum, a region dominated by the amplitude and frequency content of the ground velocity as elaborated in the following representative studies: Nau and Hall [9], Matsumura [17], Akkar and Ozen [18]. Furthermore, the intensity of near-source strong ground motions is closely related to the amplitude and number of ground velocity pulses [19–21].

Since the ground velocity is associated with the earthquake energy at the recording site, it is proposed that the significant duration of the ground motion should be related to the steep gradient of the time integral of the absolute ground velocity, instead of the Arias integral, that is based on the acceleration time history [22]

$$A_{\text{int}} = \int_0^{t_r} a_g^2 \, dt \quad (3)$$

where t_r is the total duration of the acceleration trace.

For this reason, the time integral of absolute ground velocity is introduced, in analogy with the CAV. The new index is defined as the cumulative absolute displacement (CAD):

$$\text{CAD} = \int_0^{t_r} |v_g| \, dt \quad (4)$$

The introduction of CAD, also allows a combination of the significant and bracketed durations, since the gradient of the time

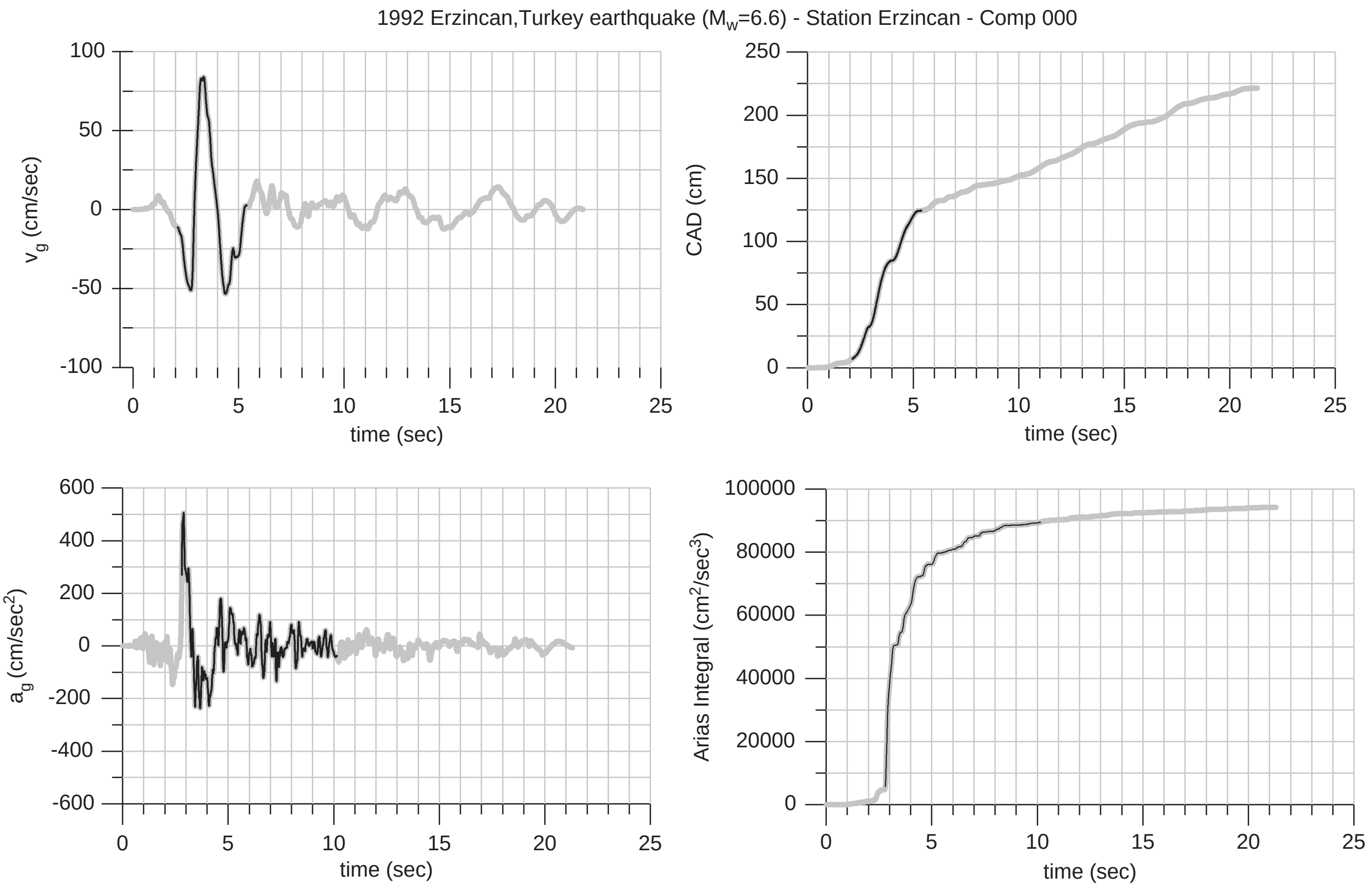

Fig. 1. Velocity and CAD time histories (grey trace) with the corresponding t_{bs} portions (black trace); acceleration; Arias integral time histories (grey trace) with the corresponding t_d portions (black trace).

integral is equal to the absolute velocity. For each ground motion, a threshold relative to a percentage of the maximum ground velocity can be defined, so that the subsequent bracketed duration coincides with the significant duration encompassing the steep gradient of the absolute velocity integral.

As described in detail in section three of this paper, a sample of well-known international strong motion records is used in order to calibrate the proposed method. For every record, a threshold is defined as a percentage of the maximum ground velocity, so that the spectral velocity values of the subsequent bracketed-significant duration t_{bs} would be at least 90% of those of the original record, in accordance with the criterion used by Trifunac and Brady [5] for the significant duration definition. The strong motion duration t_{bs} estimated for each record is compared with the duration t_d, as defined by Trifunac [5], and evaluated with the use of the Arias integral.

Furthermore, a correlation between the time-history parameters of the ground motion intensity and the response of medium and long period structures is established. As an index of the structural response, the maximum spectral velocity for 5% damping is selected with the corresponding period T_{p-v} that is closely associated with the period T_v of the pulse with the largest velocity amplitude for near-source records. The ratio between T_v and T_{p-v} has been estimated as equal to 0.84 with a standard deviation of 0.28 [23]. The period of the dominant velocity pulse T_v and the related T_{p-v} are close to the transition zone between the constant velocity and displacement regions of the response spectrum [24]. The corresponding spectral values characterize the spectral region, where the assumption of equal displacements is used for inelastic response. Consequently, the spectral velocity value $SV_{T_{p-v}}$ can be considered as an index characterizing the response of middle and long period structures.

2.2. *Structural response and time history correlation: parameters P_1 and P_2*

The present study adopts Housner's suggestion to use two parameters for the definition of ground motion severity in order to deaggregate the amplitude and duration effects for a better classification of earthquake ground motions. In order to establish a relationship between ground motion characteristics and the associated structural response, two normalized parameters P_1 and P_2 are defined. The parameters P_1 and P_2 are correlated in accordance with the well-known observation that the intensity of the elastic and inelastic structural response is associated with the number of loading cycles through which the seismic energy is distributed [25,26].

The following methodology has been employed in order to analyze selected earthquake records and estimate the normalized parameters P_1 and P_2 correlating time history and structural response quantities: (a) first, the velocity spectrum for 5% damping and for a period range between 0.02 and 10.0 s is constructed. Spectral values up to 10.0 s are included, since large magnitude events produce near-source records with predominant periods over 5.0 s [23,27], (b) the CAD integral, the Arias integral and the significant duration, as defined by Trifunac [5], are calculated, (c) based on the CAD integral and the velocity 5%

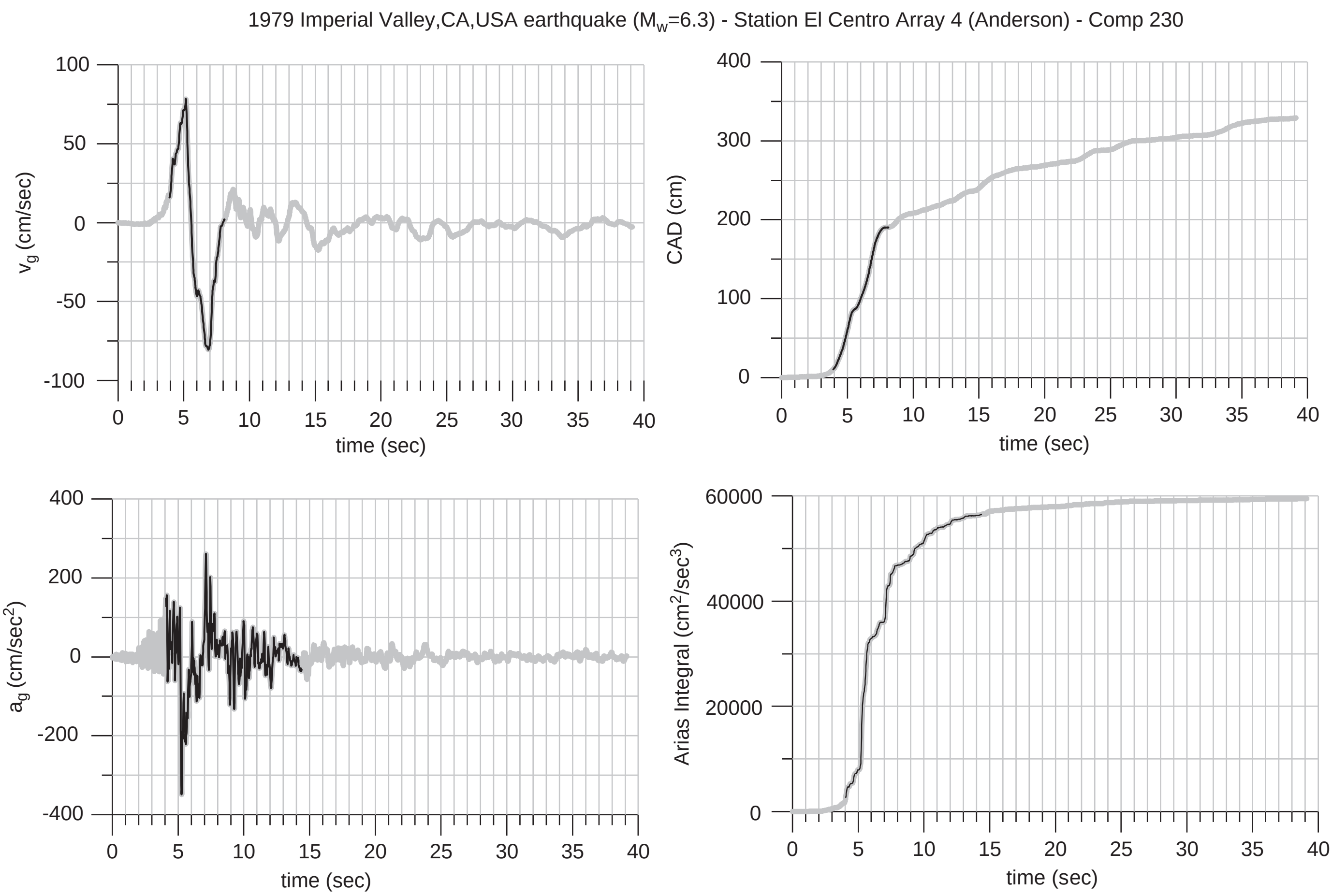

Fig. 2. Velocity and CAD time histories (grey trace) with the corresponding t_{bs} portions (black trace); acceleration; Arias integral time histories (grey trace) with the corresponding t_d portions (black trace).

spectra, the following procedure that consists of five steps is applied:

(i) Different thresholds are defined as percentages of the maximum ground velocity. For each threshold the related bracketed duration is evaluated and a relevant velocity spectrum is determined. The percentage producing the smallest bracketed duration with spectral velocity values $>$ 90% of the original has been considered as the optimum threshold for duration t_{bs}. It must be noted that regarding the spectral values, the same rule has been suggested by Trifunac [5]. For all records the duration t_{bs} evaluated by the proposed method encompasses the portion of the CAD and Arias integrals with the steepest gradient as shown in Figs. 1–4.

(ii) Once the velocity threshold and the related duration are defined, a mean velocity V_{mean} defined as the average gradient of the steep portion of the CAD integral is calculated by the following expression:

$$V_{\mathrm{mean}} = \frac{\int_{t_2}^{t_1} |v_g|\,\mathrm{d}t}{t_{bs}} \tag{5}$$

where t_1 and t_2 are the limits of the bracketed-significant duration.

(iii) From the velocity spectrum the period T_{p-v}, closely related to the duration of the maximum ground velocity pulse, and the corresponding spectral value $\mathrm{SV}_{T_{p-v}}$ are evaluated. The parameter P_1 is defined as

$$P_1 = \frac{\mathrm{SV}_{T_{p-v}}}{V_{\mathrm{mean}}} \tag{6}$$

(iv) The number of equivalent cycles P_2 is defined as the ratio

$$P_2 = \frac{t_{bs}}{T_{p-v}} \tag{7}$$

(v) The sample of P_1, P_2 values is used to draw a fitting curve that can be used to predict the structural response in the medium–long period region from velocity time-history indices.

In contrast with well-known methodologies that utilize one or two of the time-history quantities, the proposed normalized parameters P_1 and P_2 combine ground motion duration, amplitude and frequency content information; thus, allowing for a more representative consideration of the physical characteristics of the ground motion. Furthermore, the relationship between the parameters P_1 and P_2 permits to estimate the spectral values with the use of indices that have been determined directly from the velocity time histories.

3. Numerical results and discussion

The earthquake records used in this study have been selected from the COSMOS and PEER databases [28,29] according to the following criteria:

(i) the records should be related to well-known events from all over the world, so that the sample data could be considered independent of local source effects,

(ii) the events should have different levels of magnitude covering the range of medium and large earthquakes,

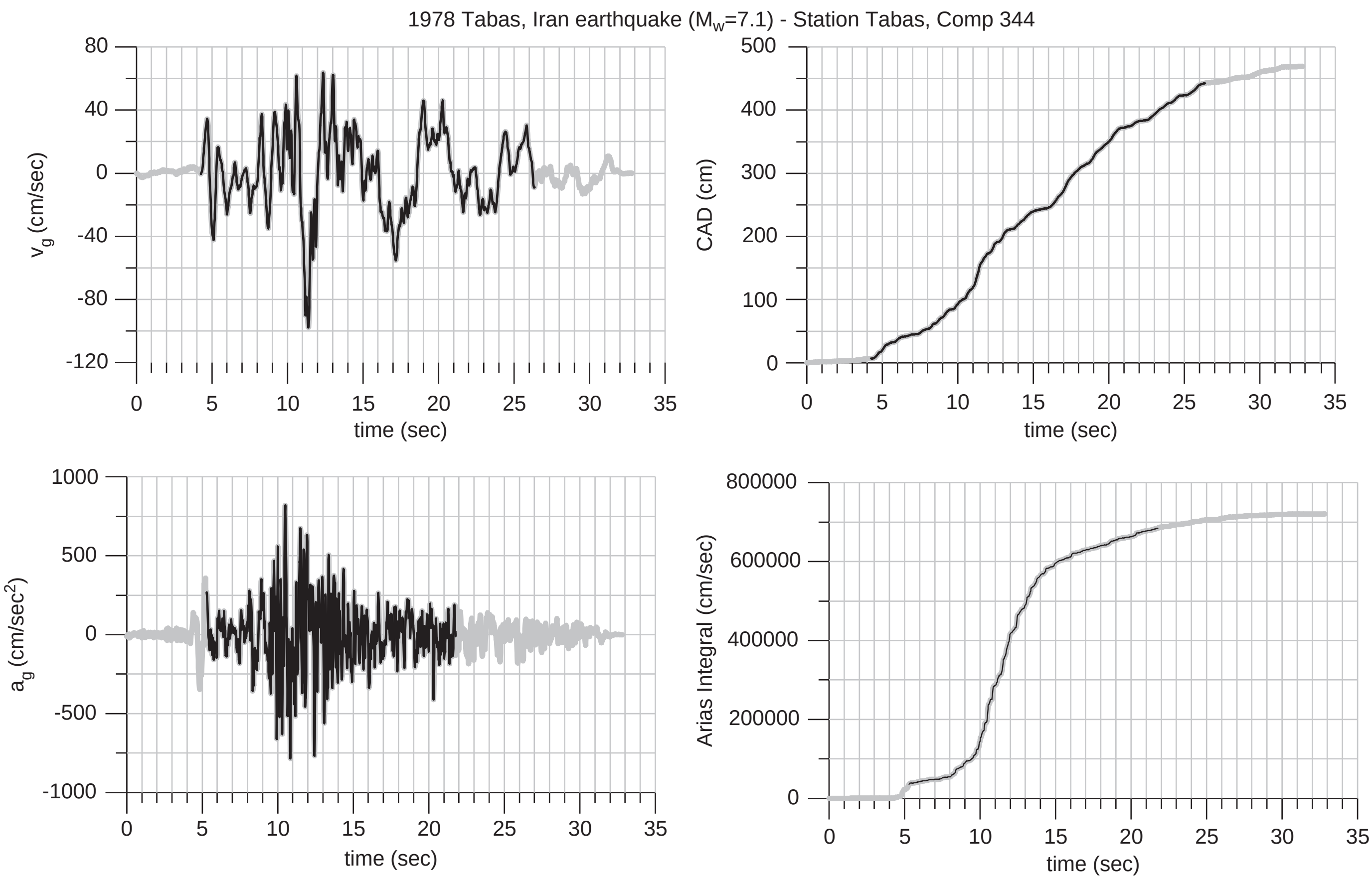

Fig. 3. Velocity and CAD time histories (grey trace) with the corresponding t_{bs} portions (black trace); acceleration; Arias integral time histories (grey trace) with the corresponding t_d portions (black trace).

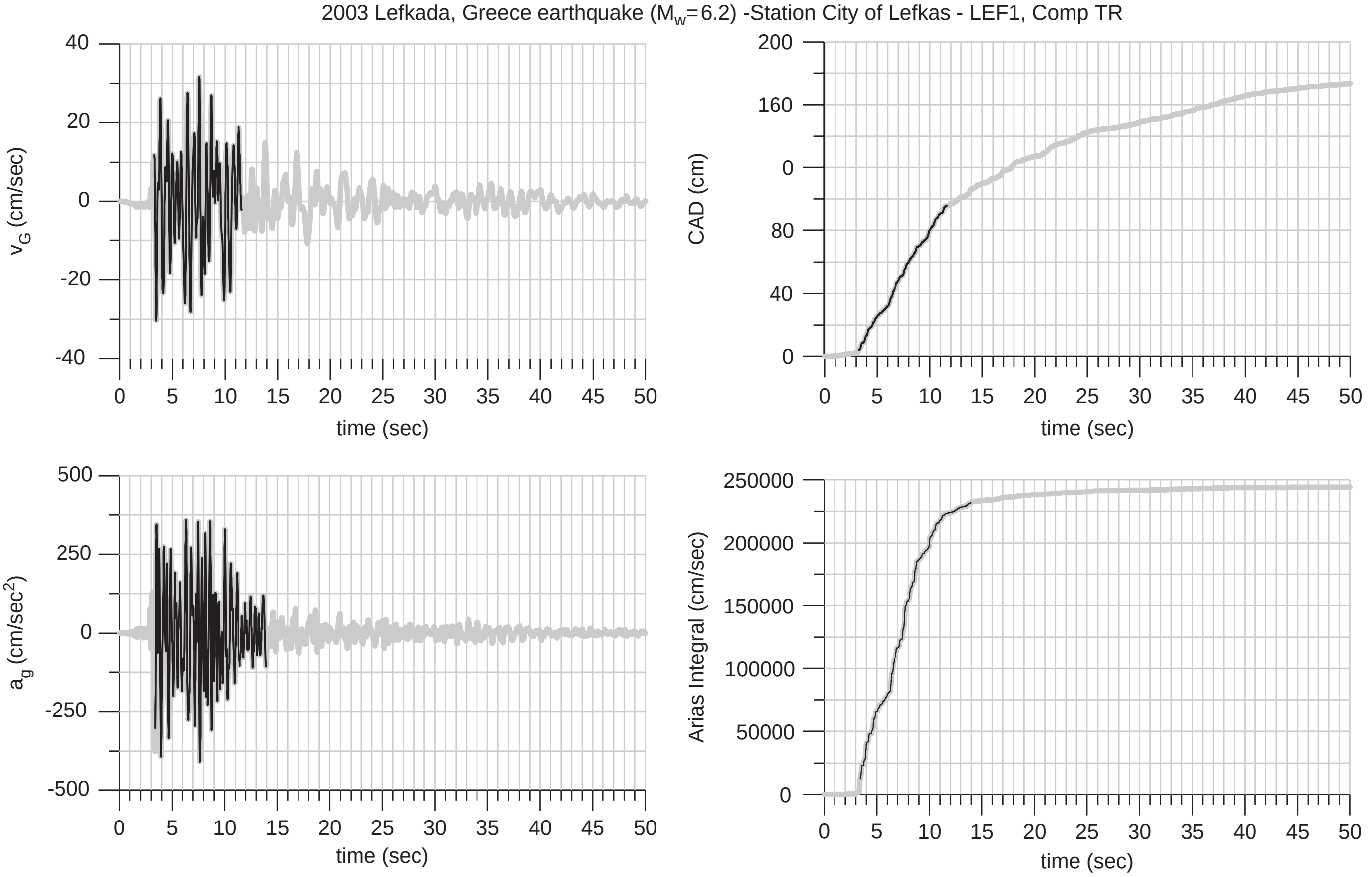

Fig. 4. Velocity and CAD time histories (grey trace) with the corresponding t_{bs} portions (black trace); acceleration; Arias integral time histories (grey trace) with the corresponding t_d portions (black trace).

Table 1
Strong motion database

No.	Location	Date	Mechanism	M_w	Station	Horizontal components	Site code	Closest distance
1	Imperial Valley, CA, USA	19-05-1940	Strike-slip[b]	6.2–6.4	El Centro—ELC	180-270	SL	8.0[ft]
2	Parkfield, CA, USA	27-06-1966	Strike-slip	6.4	Cholame Array 5—C05	355-085	SL	5.2[ft]
3	San Fernando, CA, USA	09-02-1971	Reverse	6.5–6.7	Pacoima Dam—PCD	164-254	HR	3.0[fr]
4	Gazli, USSR	17-05-1976	Reverse	6.7–6.9	Karakyr Point—KAR	000-090	SR	3.0[hc]
5	Tabas, Iran	16-09-1978	Reverse	7.1	Tabas—TAB	344-074	SL	1.2[ft]
6	Coyote Lake, CA, USA	08-06-1979	Strike-slip	5.6	Gilroy Array 1—GA1	230-320	HR	9.0[ft]
7	Imperial Valley, CA, USA	15-10-1979	Strike-slip	6.4–6.6	El Centro Array 2—E02	140-230	SL	10.4[fr]
8	Imperial Valley, CA, USA	15-10-1979	Strike-slip	6.4–6.6	El Centro Array 4—E04	140-230	SL	6.0[ft]
9	Morgan Hill, CA, USA	24-04-1984	Strike-slip[b]	6.2	Halls Valley—HAL	150-240	SL	2.0[ft]
10	Nahanni, Canada	23-12-1985	Reverse	6.7	Iverson—SITE1	010-280	HR	9.4[fp]
11	San Salvador	10-10-1986	Strike-slip	5.6	Geol. Invest. Center,Channel 1—CIG	180-270	SR	4.0[ec]
12	Whittier Narrows, CA, USA	10-10-1987	Reverse	6.0	Alhambra,Fremont Sc.—ALF	180-270	SL	13.1[fp]
13	Superstition Hills, CA, USA	24-11-1987	Strike-slip	6.4–6.6	El Centro—ELC	000-090	SL	13.6[ft]
14	Loma Prieta, USA	17-10-1989	Obverse	6.8–7.0	Gilroy Array 1—G01	000-090	SR	10.1[fp]
15	Erzincan, Turkey	13-03-1992	Strike-slip	6.6	Erzincan—ERZ	000-090	SL	2.0[ft]
16	Landers, CA, USA	28-06-1992	Strike-slip[b]	7.1–7.3	Joshua Tree—JSH	000-090	SL	11.6[ft]
17	Northridge, CA, USA	17-01-1994	Reverse	6.7–6.8	Jensen Filtration Plant—JFA	292-022	SL	5.2[fp]
18	Northridge, CA, USA	17-01-1994	Reverse	6.7–6.8	Arleta Fire Station—SFY	000-090	SL	8.0[fp]
19	Northridge, CA, USA	17-01-1994	Reverse	6.7–6.8	Sylmar Converter Station—SCH	281-011	SL	5.0[fp]
20	Northridge, CA, USA	17-01-1994	Reverse	6.7–6.8	Canoga Park Church—CPC	196-106	SL	13.7$_{fp}$
21	Northridge, CA, USA	17-01-1994	Reverse	6.7–6.8	Sun Valley Grace Church—SVG	000-090	SL	9.3[fp]
22	Hanshin (Kobe), Japan	17-01-1995	Strike-slip	6.8–6.9	Takatori—TAK	000-090	SL	1.1[ft]

Table 1 (*continued*)

No.	Location	Date	Mechanism	M_w	Station	Horizontal components	Site code	Closest distance
23	Hanshin (Kobe), Japan	17-01-1995	Strike-slip	6.8–6.9	Japanese Meteorological Agency—KJM	000-090	SL	0.6^{fr}
24	Chi-Chi, Taiwan	20-09-1999	Reverse	7.5–7.8	CHY024	000-090	SL	7.7^{fp}
25	Chi-Chi, Taiwan	20-09-1999	Reverse	7.5–7.8	CHY028	000-090	SL	2.3^{fp}
26	Duzce, Turkey	12-11-1999	Obverse	7.1	Duzce—DZC	180-270	SL	8.3^{ft}
27	Lefkada, Greece	19-08-2003	Strike-slip	6.2–6.4	City of Lefkas—LEF1	Long-trans	SL	10.0^{ec}

*The superscript b indicates backward directivity effects.

**The following superscripts indicate: ft, distance from fault trace; fr, distance from fault rupture; fp, distance from fault plane; ec, epicentral distance; hc, hypocentral distance.

***The following site codes indicate: SL, soil and alluvium; SR, sedimentary and conglomerate rock; HR, hard rock.

Table 2
Parameters obtained from strong motion database

No.	Record	t_d	max v_g	Fajfar's index	Threshold % of max v_g	t_{bs}	$\int^{t_{bs}} \lvert v_g \rvert dt$	V_{mean}	T_{v-p}	$SV_{T_{p-v}}$	P_1	P_2
1	ELC-180	24.10	29.69	65.78	30	25.20	137.57	5.46	1.0	88	16.12	25.20
2	ELC-270	23.49	29.66	65.30	30	26.62	166.66	6.26	2.0	80	12.78	13.31
3	C05-355	7.44	21.77	35.95	30	8.10	31.79	3.92	0.4	65	16.56	20.25
4	C05-085	6.45	24.63	39.25	30	7.99	47.99	6.01	0.4	78	12.99	19.97
5	PCD-164	7.04	112.49	183.23	30	7.08	194.08	27.41	1.4	220	8.03	5.06
6	PCD-254	7.26	54.13	88.85	30	6.96	99.63	14.31	0.5	200	13.97	13.92
7	KAR-000	6.40	65.37	103.97	30	6.62	151.65	22.91	4.5	145	6.33	1.47
8	KAR-090	6.84	71.57	115.74	30	6.79	128.81	18.97	4.0	120	6.33	1.70
9	TAB-344	16.48	97.75	196.95	30	22.10	436.00	19.73	5.6	160	8.11	3.95
10	TAB-074	16.12	121.22	242.89	30	15.42	529.76	34.36	4.8	340	9.90	3.21
11	GA1-230	7.31	3.37	5.54	30	7.45	5.53	0.74	1.0	9	12.12	7.45
12	GA1-320	5.77	8.24	12.77	25	2.78	5.97	2.15	1.0	16	7.45	2.78
13	E02-140	9.06	33.67	58.42	35	13.60	115.97	8.53	2.0	90	10.55	6.80
14	E02-230	12.20	32.75	61.21	35	21.62	160.56	7.43	5.2	60	8.08	4.16
15	E04-140	6.72	38.24	61.57	30	14.32	147.93	10.33	2.0	108	10.45	7.16
16	E04-230	10.32	80.50	144.28	30	4.18	179.98	43.06	4.0	170	3.95	1.04
17	HAL-150	15.30	12.51	24.74	30	16.15	45.86	2.84	0.8	42	14.79	20.19
18	HAL-240	10.65	39.37	71.12	45	1.16	17.21	14.84	0.8	80	5.39	1.45
19	SITE1-010	7.90	45.88	76.92	30	8.70	80.66	9.27	4.0	75	8.09	2.17
20	SITE1-280	8.07	46.07	77.65	30	9.02	100.45	11.14	4.0	75	6.73	2.25
21	CIG-180	6.26	56.92	90.03	30	2.54	61.17	24.08	2.4	110	4.57	1.06
22	CIG-270	4.96	73.11	109.11	30	1.76	41.96	23.84	0.8	190	7.97	2.20
23	ALF-180	5.27	21.96	33.27	30	2.95	21.28	7.21	0.9	65	9.01	3.28
24	ALF-270	5.75	16.29	25.23	20	9.58	32.65	3.41	1.2	38	11.15	7.98
25	ELC-000	16.04	46.35	92.76	30	25.78	177.13	6.87	1.4	90	13.10	18.41
26	ELC-090	19.04	40.86	85.35	30	22.63	185.73	8.21	2.2	105	12.79	10.29
27	G01-000	6.53	31.56	50.45	30	2.85	18.6	6.53	0.4	70	10.73	7.13
28	G01-090	3.68	33.86	46.90	30	2.62	31.70	12.10	0.4	125	10.33	6.55
29	ERZ-000	7.46	83.95	138.74	30	3.26	117.37	36.00	2.4	180	5.00	1.36
30	ERZ-090	7.35	64.28	105.84	30	7.87	134.00	17.03	3.4	115	6.75	2.31
31	JSH-000	27.22	27.45	62.70	45	23.74	158.56	6.68	1.1	100	14.97	21.58
32	JSH-090	26.06	43.05	97.27	35	26.64	235.62	8.84	1.1	125	14.13	24.22
33	JFA-292	5.98	99.10	154.97	30	6.04	200.92	33.26	3.0	250	7.52	2.01
34	JFA-022	12.38	105.99	198.81	30	6.70	214.22	31.97	2.0	290	9.07	3.35
35	SFY-000	13.54	22.74	43.62	30	21.84	132.46	6.07	3.0	72	11.87	7.28
36	SFY-090	13.12	39.34	74.87	30	12.32	96.44	7.83	1.0	90	11.50	12.32
37	SCH-281	7.52	74.57	123.49	35	3.60	97.25	27.01	2.0	200	7.40	1.80
38	SCH-011	6.90	117.49	190.42	30	4.94	142.96	28.94	4.0	175	6.05	1.24
39	CPC-196	12.14	64.23	119.89	25	11.38	145.32	12.7	2.2	150	11.75	5.17
40	CPC-106	14.86	39.66	77.87	35	16.16	145.24	8.99	2.0	100	11.13	8.08
41	SVG-000	13.88	23.34	45.05	30	26.68	142.13	5.33	1.2	75	14.08	22.23
42	SVG-090	16.82	40.85	82.73	30	22.16	177.34	8.00	1.2	110	13.75	18.47
43	TAK-000	11.35	127.19	233.45	30	12.44	430.39	34.60	2.0	390	11.27	6.22
44	TAK-090	9.93	120.72	214.30	30	8.87	305.71	34.47	2.0	300	8.70	4.43
45	KJM-000	8.36	81.30	138.24	30	6.14	174.48	28.42	0.8	260	9.15	7.67
46	KJM-090	9.52	74.35	130.60	30	8.26	146.02	17.68	0.8	240	13.58	10.32
47	CHY024-000	21.65	49.01	105.72	30	22.38	294.58	13.16	5.2	140	10.64	4.30
48	CHY024-090	21.05	52.90	113.31	30	18.12	275.35	15.20	4.2	135	8.88	4.31
49	CHY028-000	5.65	66.94	103.20	30	7.68	156.89	20.43	1.0	220	10.77	7.68
50	CHY028-090	7.74	72.14	120.33	30	6.41	131.79	20.56	2.0	180	8.75	3.21
51	DZC-180	10.94	59.99	109.10	35	12.94	287.12	22.19	5.8	170	7.66	2.23
52	DZC-270	10.78	83.50	151.30	30	12.49	338.58	27.11	5.2	205	7.56	2.40
53	LEF1-LN	15.16	29.59	58.39	30	14.57	99.98	6.86	0.6	115	16.76	24.28
54	LEF1-TR	10.55	31.58	56.91	50	8.33	91.77	11.02	0.6	155	14.07	13.88

(iii) the records should be collected from sites with different soil conditions and source distances,
(iv) records from earthquakes with short, medium and long significant durations should be included,
(v) different directivity effects should be taken into account.

The data sample includes well-known earthquakes, such as the Northridge (1994), the Kobe (1995) and the Chi-Chi (1999) events.

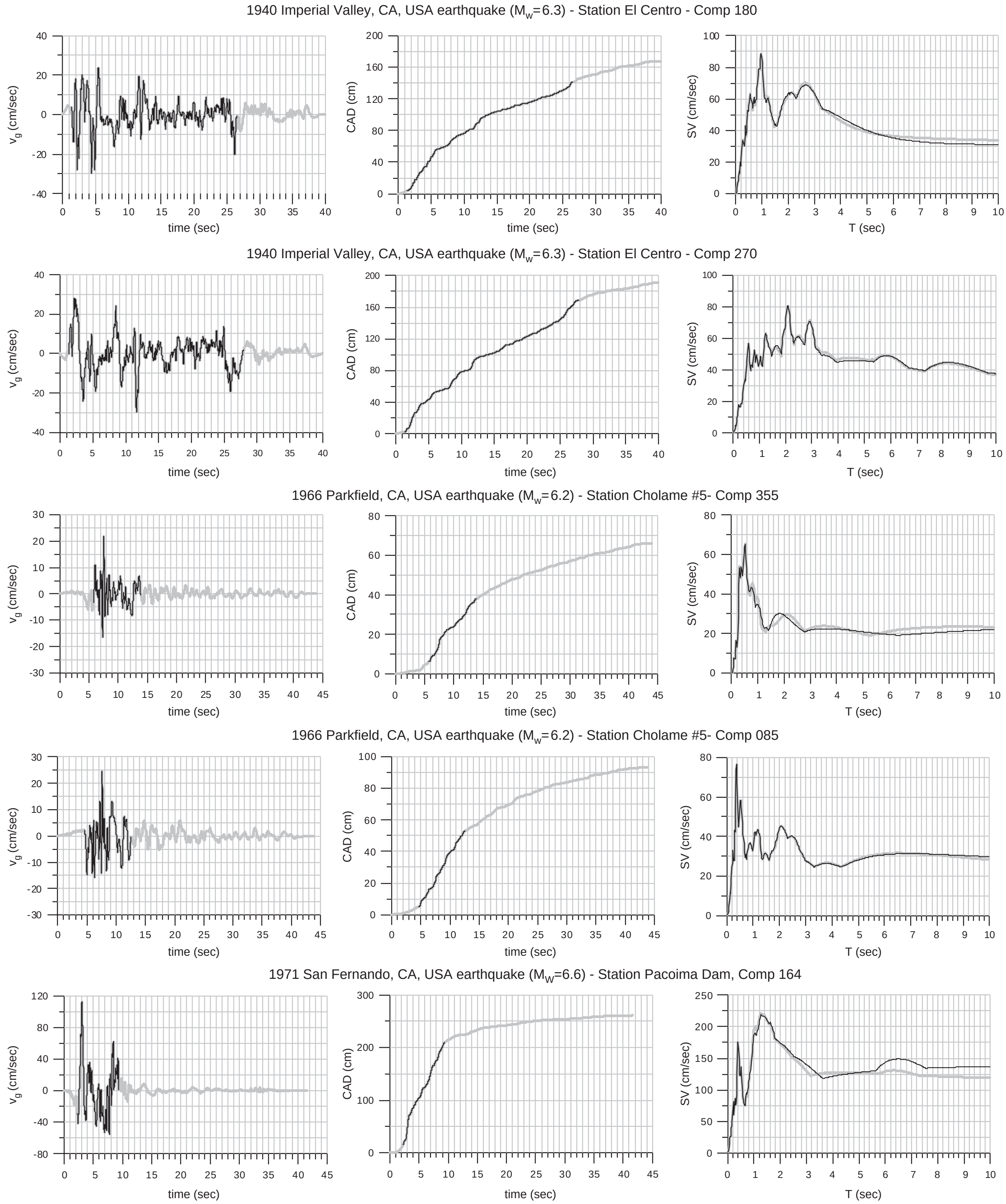

Fig. 5. Velocity and CAD time histories of the relevant component (grey trace) with the corresponding t_{bs} portion (black trace); and the spectra corresponding to the whole duration (grey trace) and the t_{bs} portion (black trace).

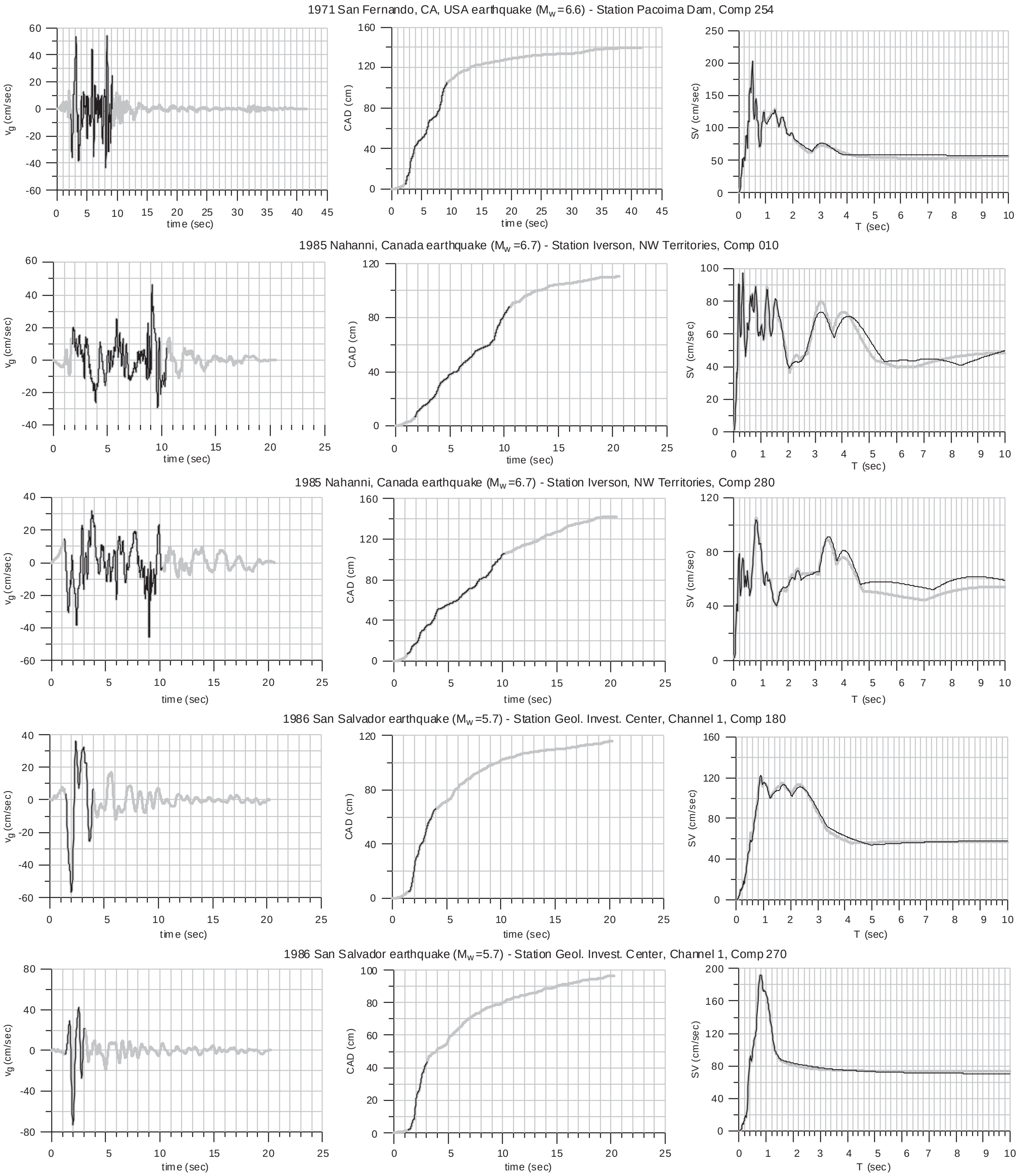

Fig. 5. (*Continued*)

The magnitude, record stations and source distances for the records are given in Table 1. The San Salvador earthquake of 1986 is included to account for small-to-moderate events with near-source effects [30]. An earthquake from the Island of Lefkada is also included in order to enhance the long duration data of the sample [31]. The corrected data are used as given in the relative databases and no further filtering is undertaken.

For each one of the 54 selected records, the P_1 and P_2 normalized parameters and the associated peak ground velocity, the t_{bs} and t_{d} durations, the V_{mean}, the T_{p-v} period and $\mathrm{SV}_{T_{p-v}}$ spectral value are evaluated and the results are presented in Table 2.

For near-source records, with a few strong velocity pulses that are associated with the steep gradient of the velocity integral, t_{bs}

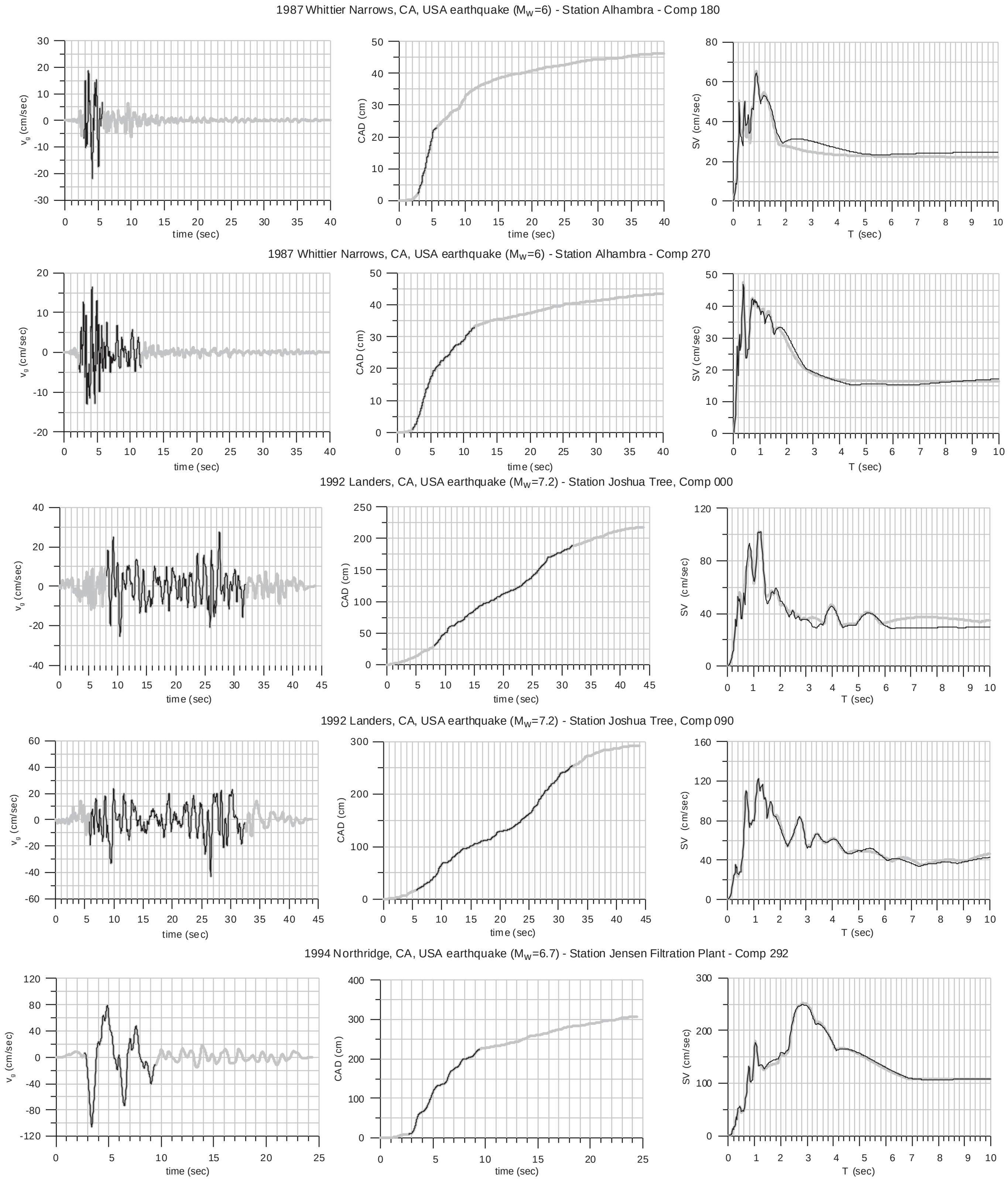

Fig. 5. (*Continued*)

is closer to the total duration of the velocity cycles than the t_d significant duration, as shown in Table 2. Figs. 1 and 2 show characteristic examples of the t_{bs} and t_d durations for the ERZ-000 record of the Erzincan (Turkey, 1984) and the E04-230 record of the Imperial Valley (USA, 1979) events, where the bracketed-significant duration is quite shorter than the Trifunac duration, 3.26 and 4.18 s versus 7.46 and 10.32 s, respectively. Thus, it can be stated that the definition of t_{bs} gives better correlated results with the intense part of the strong motion; since, for near-source events with forward directivity, the significant part of the record is related to a limited number of velocity cycles [19–21,27]. Another significant observation that should be made is related to the

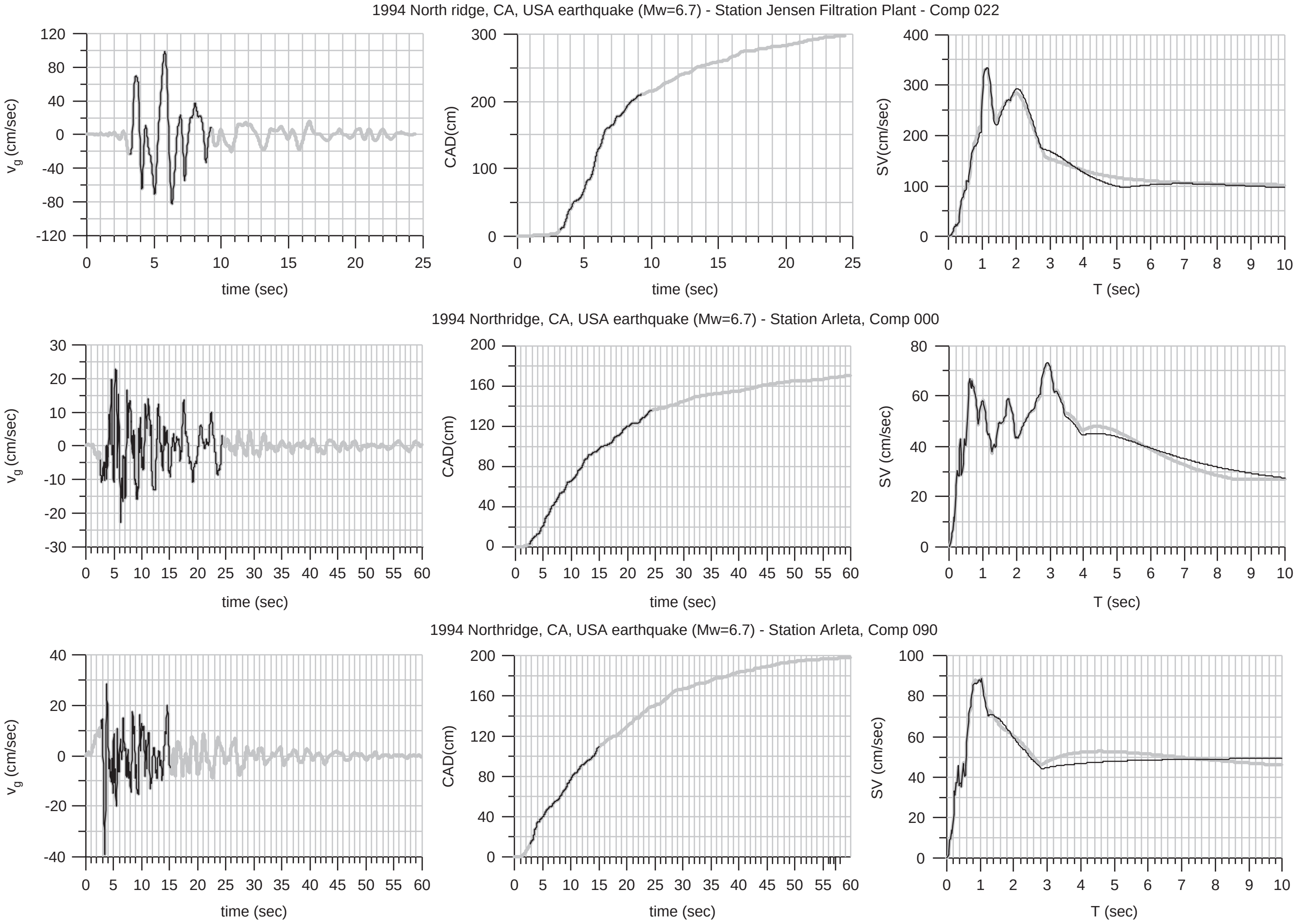

Fig. 5. (*Continued*)

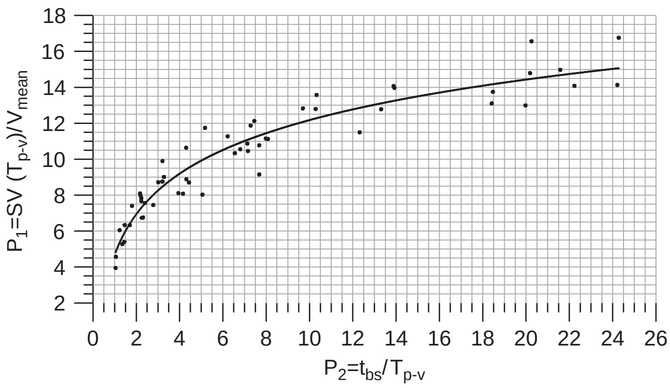

Fig. 6. Variation of the amplitude parameter P_1 with the equivalent number of cycles P_2.

percentage of the ground velocity, used as a threshold to evaluate the t_{bs}. As listed in the related column of Table 2, the percentage is usually about 30% of the maximum ground velocity for most cases. This percentage can be proposed as the threshold for the estimation of the V_{mean} gradient of the CAD integral.

In certain cases, e.g., the TAB-344 record of the Tabas (Iran, 1978) earthquake, t_{bs} is longer than t_d, as shown in Fig. 3. The fact can be attributed to the longer period component being much more pronounced in the velocity than in the acceleration time history. As a result, the intense portion of the CAD integral can be longer than that of the Arias integral associated with the squared acceleration, especially when the CAD gradient is not very steep. Generally the duration t_{bs} is similar or shorter than t_d, especially for near-source records.

Fig. 5 shows, for several of the sample records that the velocity spectra calculated for the t_{bs} and total durations are almost identical. Since the velocity spectrum is related to the energy of the excitation [32,33], it can be stated that the energy content of the intense part of the ground motion is practically equivalent to the total energy release.

From Fig. 6, it is observed that the amplification parameter P_1 tends to an asymptotic value as the number of cycles increases, a phenomenon very similar to the amplification of the structural response for increasing cycles of harmonic loading [34]. A fitting curve is also drawn in Fig. 6 for the sample data, presenting a coefficient of determination 0.91. The maximum residual in the sample, as a percentage of the predicted value, is $<20\%$. The least-squares fitting curve is given by the following expression:

$$P_1 = 3.23 \times \ln(P_2) + 4.61 \tag{8}$$

The P_1 that is <8 is associated with near-source records characterized by up to two or three strong velocity cycles in the strong motion part of the record. However, large P_1 values, i.e., greater than 12, are associated with either records on soft soils, such as the LEF1-TR record of the LEUKADA (2003) earthquake, or records associated with backward directivity effects, such as the ELC-180 (Imperial Valley, USA, 1940), the HAL-150 (Morgan Hill, USA, 1984) and the JSH-000, JSH-090 (Landers, USA, 1992). All

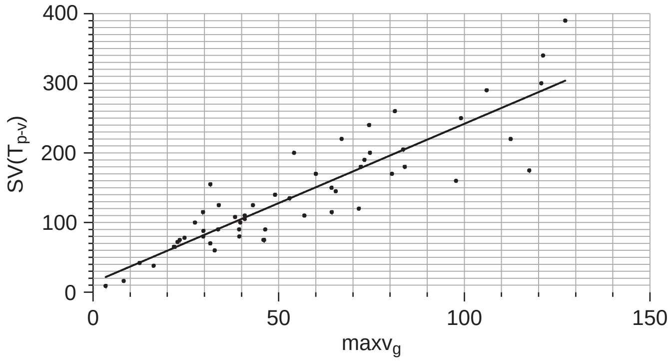

Fig. 7. Variation of spectral velocity SV(T_{p-v}) with max v_g.

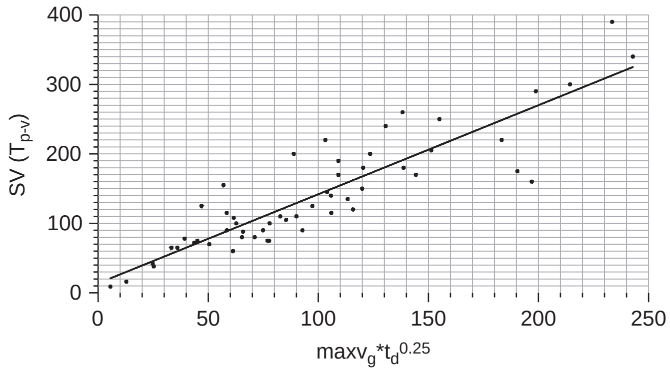

Fig. 8. Variation of spectral velocity SV(T_{p-v}) with Fajfar's index.

these records are characterized by a large number of significant velocity cycles.

Fig. 7 presents the SV$_{T_{p-v}}$ variation in terms of max v_g, based on the Nau and Hall remarks [9] that the use of max v_g as a scaling parameter presents the greatest reduction in the response variation of medium-to-long structures for different ground motions. Fig. 8 depicts the SV$_{T_{p-v}}$ variation in terms of the index introduced by Fajfar et al. [13], that combines max v_g and duration t_d. Furthermore, in Figs. 7 and 8, least-squares fits are drawn with coefficients of determination about 80%. Notice that the residuals of the sample values are very pronounced, that is, more than 40%, of the predicted value, especially for records presenting a large number of strong velocity pulses, such as the LEF1-TR (Lefkada, Greece, 2003). It can be stated that the proposed parameters and their relationship present a better fit over the whole range of earthquake events.

4. Conclusions

This study introduces a new definition of the strong ground motion duration combining well-established definitions of bracketed and significant durations. Instead of the squared acceleration and the associated Arias integral, the time integral of the absolute velocity is adopted as the pertinent parameter. Since the gradient of the integral is equal to the absolute velocity time function, use of a percentage of the maximum absolute velocity, as a threshold, defines a bracketed duration containing the significant part of the ground motion. The significant duration encompasses the steep portion of the absolute velocity integral, expressed as CAD in analogy with the well-known cumulative absolute velocity (CAV) index.

The bracketed-significant duration t_{bs} is found to be similar to the Trifunac duration. In what regards near-source strong motions, t_{bs} is quite smaller than t_d, coinciding with the duration of the strong velocity pulses that dominate this type of records. Consequently, it can be stated that the proposed definition shows a better correlation with the duration of intense energy release at the recording site. For most of the sample records the threshold percentage is estimated to be close to 30% of the maximum ground velocity.

An index associated with the damage of medium and longer period structures is defined as the maximum spectral velocity SV$_{T_{p-v}}$ for 5% damping at a period T_{p-v} which is closely related to the duration of the peak ground velocity pulse.

Two normalized parameters, P_1 and P_2, are introduced. The parameters P_1 and P_2 permit a good approximation of the structural response in the medium-to-long period range with the aid of the indices t_{bs}, CAD and T_{p-v} that are directly estimated from the ground velocity time histories.

An exponential fitting curve for a data sample calculated from 54 earthquake records is established. It has been found that the coefficients of determination between SV$_{T_{p-v}}$and the max v_g and Fajfar indices are less than the coefficient of determination between the newly proposed parameters P_1 and P_2, and the residuals for records with a large number of strong velocity pulses are more pronounced.

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