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 the cumulative absolute displacement CAD. The index is used in order to evaluate the strong motion duration. The proposed bracketed-significant duration is well correlated with the strong motion part of the records, especially in the case of near-source events. The duration and the CAD index are correlated with the structural behaviour of medium-to-long period structures. Two normalized parameters representing the amplification of structural response and the number of equivalent loading cycles are determined in terms of the proposed duration and CAD indices. The proposed parameters appear to be better correlated with the structural response than other well-known indices.

KEYWORDS: ground motion significant duration, near-fault records, damage indices

1. INTRODUCTION

Earthquake strong ground motion is a complex natural phenomenon associated with the abrupt energy release during fault rupture. The intensity of the seismic event can be described in terms of the perceived effects of ground motion according to different intensity scales. The availability of strong ground motion records permits a consistent use of quantitative indices based on the amplitude, duration and frequency content of the earthquake records. The most frequently used intensity indices are the peak ground acceleration and velocity, the significant duration of the strong motion as defined by Trifunac and Brady (1975) and the spectral values for different characteristic periods of the strong motion records. In his pioneering work, Housner (1975) proposed the combination of at least two parameters in order to define a reliable severity index. The selected parameters should be related to the duration and the average energy release of the intense part of the ground motion. According to Housner, 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 strong motion, and the duration of the steep gradient interval are considered to be associated with the duration and average rate of intense energy release and the severity of the seismic hazard at the recording site.

Trifunac and Brady (1975) defined as the significant duration of the strong ground motion the time interval between the 5% and the 95% of the Arias intensity (1970). The selection of the referred limits was based on the criterion that the spectral values calculated for the significant duration interval should not be less than 90% of the values given for the total duration of the record. However, there is still not a consensus on the definition of the significant duration of strong ground motion. A similar definition by Bommer and Pereira (1999) proposes, as effective duration, the time interval between two particular thresholds of the Arias intensity. Alternative definitions of bracketed duration (Kawashima and Aizawa, 1989), 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.

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:

- the mean square, root square and root-mean –square of the squared acceleration, velocity and displacement integrals that are associated with the intense energy release and are considered as the effective values of the ground motion amplitude,
- the incremental velocity (IV) and incremental displacement (ID) calculated by integrating the individual pulses of the acceleration and velocity time-histories respectively (Anderson and Bertero, 1987),
- the cumulative absolute velocity (CAV), that is, the integral of the absolute acceleration over the ground motion duration (EPRI, 1991),
- the characteristic intensity (CI) proposed by Ang (1990)
- the index proposed by Fajfar *et al.* (1990),

$$F_1 = \max v_g \cdot t_d^{0.25} \tag{1.1}$$

where max v_g is the peak ground velocity and t_d the duration according to Trifunac and Brady (1975).

The referred indices combine amplitude and duration of the ground motion time histories in order to account for earthquake intensity. Cabanas *et al.* (1997) state that the estimation of structural response considering both amplitude and duration produces better results in what regards the damage potential of earthquakes.

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 distinct 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 equivalent velocity cycles, is another parameter affecting the intensity of strong ground motion. 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 instead of the ground acceleration, as elaborated in the following representative studies by Nau and Hall (1984), Matsumura (1992) and Akkar and Özen (2005). Furthermore, the intensity of near source strong ground motions is closely related to the amplitude and number of ground velocity pulses.

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 velocity, instead of the Arias integral (1970). For this reason, the time integral of absolute ground velocity is introduced, in analogy with the already established definition of the cumulative absolute velocity CAV (EPRI, 1991). The new index is defined as the cumulative absolute displacement, CAD:

$$CAD = \int_0^{tr} \left| v_g \right| dt \tag{2.1}$$

where t_r is the total duration of the acceleration trace.

The introduction of CAD, also allows a combination of the definitions of the significant and bracketed duration. 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.

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 (1975) 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 and Brady.

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 spectral velocity for 5% damping corresponding to the predominant period $T_{d\text{-}p}$ of the displacement spectrum is selected. The period $T_{d\text{-}p}$ is closely associated to the period T_p of the directivity pulses contained in the velocity time-history, according to Mavroeidis *et al.* (2004). The period T_p defines the region of increased ductility demand and is close to the transition zone between the constant velocity and displacement regions of the response spectrum. Consequently, the spectral velocity $SV_{Td\text{-}p}$ can be considered as an index characterizing the response of middle and long period structures.

2.2. Structural Response and Time History Correlation

In order to establish a relationship between ground motion characteristics and the associated structural response, as expressed by $SV_{Td\text{-}p}$, two normalized parameters P_1 and P_2 are defined. The parameter P_1 is associated with the equivalent number of loading cycles contained in the time-history of ground velocity. According to Rodriguez-Marek (2000) the mean period of the individual velocity pulses of the ground velocity is very well correlated with the period T_p. Subsequently, in accordance with the indirect counting method, the equivalent number of cycles P_1 can be defined as the ratio:

$$P_1 = \frac{t_{bs}}{T_{d-p}} \tag{2.2}$$

The relation between strong motion duration and structural response is associated, according to Housner (1975), with the effective amplitude of the strong motion interval of a record. This study adopts as a measure of the effective amplitude of the ground motion a velocity value defined as a mean or effective velocity V_{mean} equal to the average gradient of the steep portion of the CAD integral and calculated by the following expression:

$$V_{mean} = \frac{\int_{t_1}^{t_2} \left| v_g(t) \right| dt}{t_{bs}} \tag{2.3}$$

where t_1 and t_2 are the limits of the bracketed-significant duration t_{bs}.
A second normalized parameter P_2, relating the structural response $SV_{Td\text{-}p}$ and the effective ground velocity

amplitude V_{mean}, is defined as:

$$P_2 = \frac{SV_{T_{d-p}}}{V_{mean}} \tag{2.4}$$

This ratio presents a spectral amplification referring to the effective instead of the peak value of the ground velocity time history.

2.3. Description of Methodology

The following methodology has been employed in order to estimate the normalized parameters P_1 and P_2 correlating time history and structural response quantities: a) first, for each record, the velocity and displacement spectra for 5% damping are constructed, b) the CAD integral is calculated, c) based on the CAD integral and the 5% velocity 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 defined. The percentage producing the smallest duration with spectral velocity values greater than 90% of the original has been considered as the optimum threshold for duration t_{bs}. The duration t_{bs} evaluated by the proposed method encompasses the portion of the CAD integral with the steepest gradient.

ii) Once the velocity threshold and the related duration are defined, the effective velocity V_{mean} is calculated by Eqn. 2.3.

iii) From the displacement spectrum the period T_{d-p} and from the velocity spectrum the corresponding spectral value SV_{Td-p} are evaluated. The parameter P_2 is defined following Eqn. 2.4.

iv) The number of equivalent cycles P_1 is calculated by Eqn. 2.2.

v) The sample of P_1 and P_2 values is used to draw a fitting curve that presents the relation between the structural response in the medium-long period region and ground velocity time-history indices. The proposed normalized parameters P_1 and P_2 combine ground motion duration, effective amplitude and frequency content information with structural response.

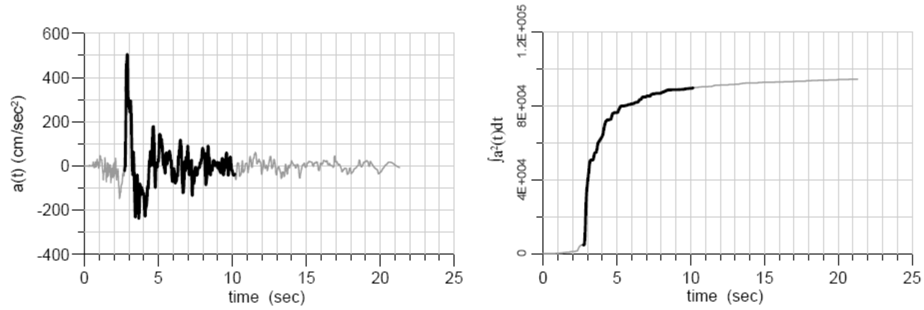
3. NUMERICAL RESULTS AND DISCUSSION

The earthquake records used in this study have been selected from the COSMOS and PEER databases. The records should be related to well known events from all over the world, with different levels of magnitude and short, medium and long significant durations. The sites of the recording stations present different soil conditions and source distances. Different directivity effects were taken into account. The data sample includes well-known earthquakes, such as the Northridge (USA, 1994), the Kobe (Japan, 1995) and the Chi-Chi (Taiwan, 1999) events. For near source records, with a few strong velocity pulses, t_{bs} is closer to the duration of the strong velocity pulses than the t_d significant duration. Figures 1 and 2 show characteristic examples of the t_{bs} and t_d durations for the ERZ-000 record of the Erzincan (Turkey, 1992) and the E04-230 record of Imperial Valley (USA, 1979) events. Another significant observation is that the percentage of the peak ground velocity, used as a threshold to evaluate the t_{bs}, is usually about 30%.

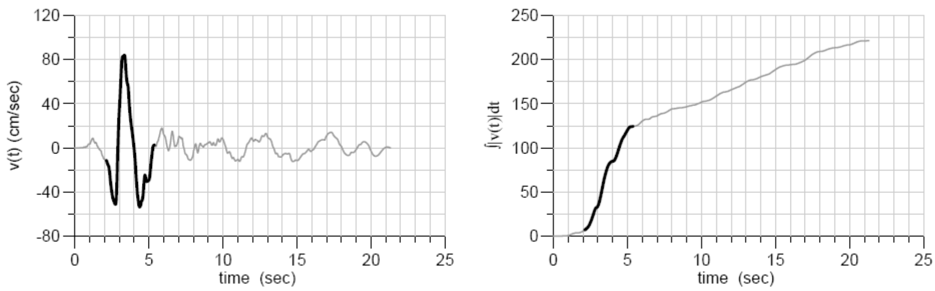
Figure 3.1 presents the sample and the fitting curve of the P_1 and P_2 values. It is observed that the amplification parameter P_2 tends to an asymptotic value as the number of cycles increases, a phenomenon very similar to the amplification of the structural response for increasing cycles of harmonic loading. The fitting curve presents a correlation coefficient of 90%. The maximum residual in the sample, as a percentage of the predicted value, is less than 30% as shown in figure 4.1. The least squares fitting curve is given by the following expression:

$$P_2 = 3.33 \cdot \ln(P_1) + 4.28 \tag{3.1}$$

The values of parameter P_2 are small when associated with near source records characterized by up to two or three strong velocity cycles. Greater P_2 values are associated with records presenting backward directivity effects characterized by a large number of significant velocity pulses.

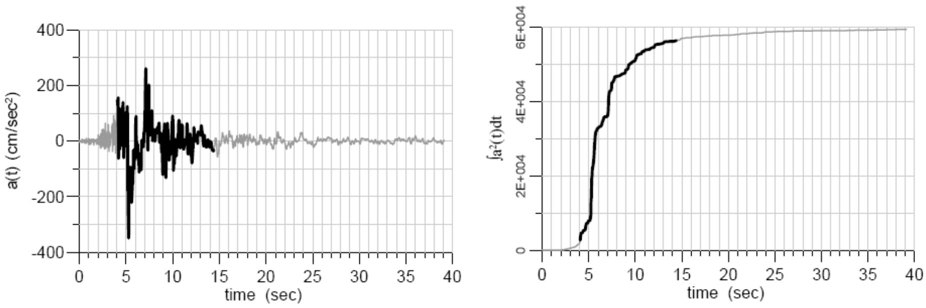


(1.1) **(1.2)**

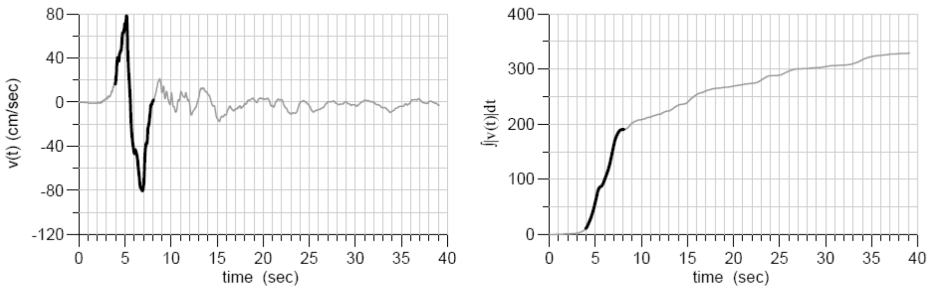


(1.3) **(1.4)**

Figure 1 ERZ-000 component (Erzincan, Turkey, 1992): **(1.1)** Acceleration time history and **(1.2)** Arias integral with the corresponding significant duration t_d portion (black trace), **(1.3)** Velocity time history and **(1.4)** CAD integral with the corresponding bracketed-significant duration t_{bs} portion (black trace)



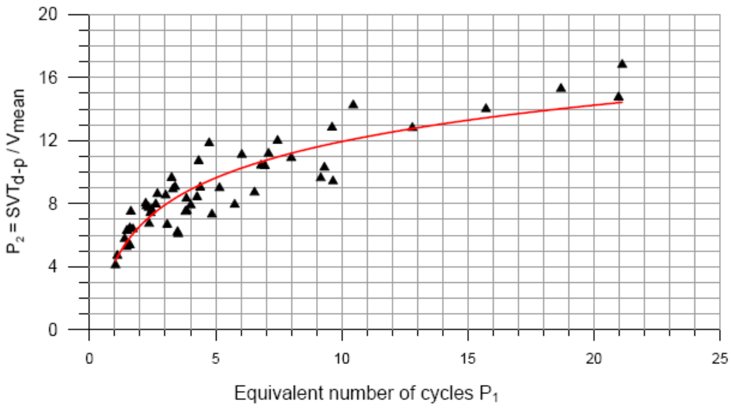
(2.1) **(2.2)**



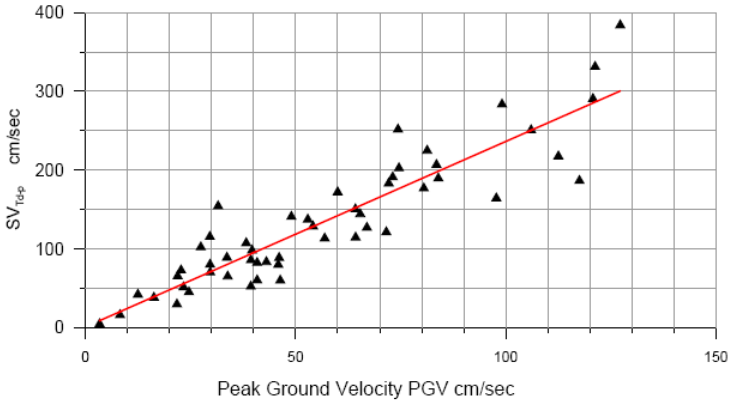
(2.3) **(2.4)**

Figure 2. E04-230 component (El Centro Array 4 Station, Imperial Valley, USA, 1979): **(2.1)** Acceleration time history and **(2.2)** Arias integral with the corresponding significant duration t_d portion (black trace), **(2.3)** Velocity time history and **(2.4)** CAD integral with the corresponding bracketed-significant duration t_{bs} portion (black trace)

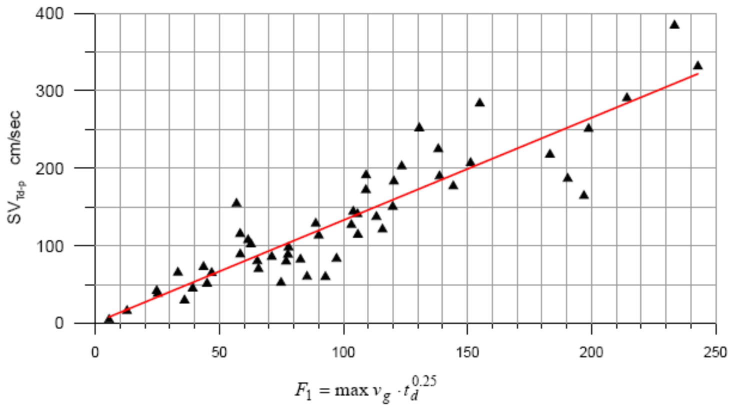
In order to evaluate the efficiency of the proposed parameters, the correlation between structural response and well established indices as the peak ground velocity and the index presented by Fajfar *et al.* (1990) is estimated. Figures 3.2 and 3.3 depict the SV_{Td-p} variation in terms of max v_g and the index introduced by Fajfar *et al.* (1990) respectively. The least square fits are drawn with correlation coefficients about 90%, similar to that of the proposed parameters P_1 and P_2. The related residuals, presented in Figures 4.2 and 4.3, are greater than 50% of the predicted values, especially for records with backward directivity effects. Furthermore, the residuals appear to be related to the number of equivalent cycles P_1. The index introduced by Fajfar *et al.* (1990) is less related to P_1 since the significant duration is taken into account. The residuals regarding the P_1 and P_2 values are not related to the number of equivalent cycles, as presented in Figure 4.1.



(3.1)

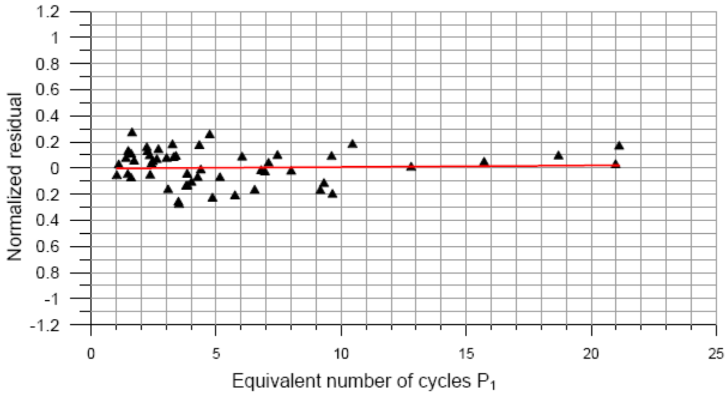


(3.2)

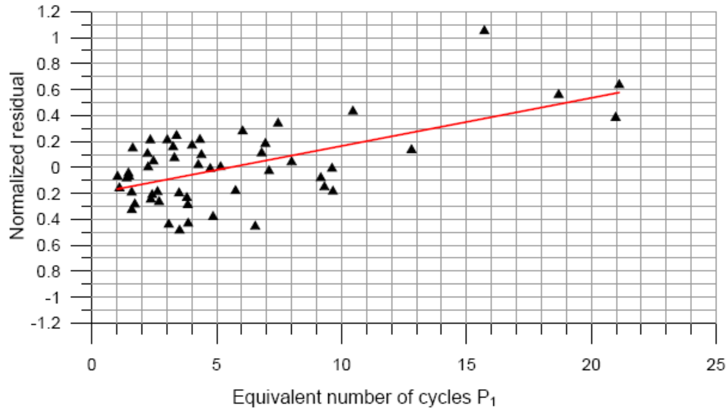


(3.3)

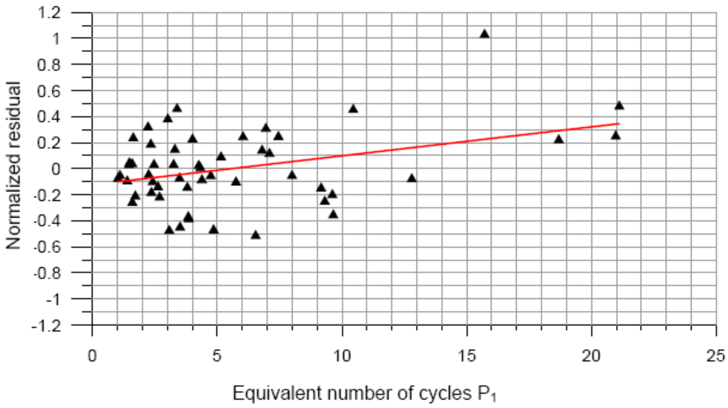
Figure 3. Correlation between: **(3.1)** the amplitude parameter P_2 and the equivalent number of cycles P_1, **(3.2)** spectral velocity SV_{Td-p} and max v_g, **(3.3)** spectral velocity SV_{Td-p} and F_I index



(4.1)



(4.2)



(4.3)

Figure 4. Correlation between the equivalent number of cycles P_1 and the normalized residuals: **(4.1)** of figure (3.1), **(4.2)** of figure (3.2), **(4.3)** of figure (3.3)

3. CONCLUSIONS

This study introduces a new definition of strong motion duration combining well established definitions of bracketed and significant durations. Instead of the Arias integral, the time integral of the absolute velocity is adopted as the pertinent parameter. A percentage of the maximum absolute velocity, used as a threshold, defines a bracketed duration containing the significant part of the ground motion. For most of the sample records the threshold percentage is estimated to be close to 30% of the maximum ground velocity. The significant duration encompasses the steep portion of the absolute velocity integral, expressed as cumulative absolute displacement

CAD.The bracketed-significant duration $t_{bs,}$ for near source strong motions, is quite smaller than $t_{d,}$ coinciding with the duration of the strong velocity pulses that dominate this type of records.

An index associated with the response of medium and longer period structures is defined as the maximum spectral velocity SV_{Td-p} for 5% damping at the period T_{d-p} which is closely related to the period of the ground velocity directivity pulses. 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_{d-p} that are associated with the ground velocity time-histories.

An exponential fitting curve for a data sample calculated from 54 earthquake records is established. The correlation between SV_{Td-p} and the peak ground velocity and Fajfar *et al.* (1990) indices are evaluated. The correlation coefficients are found to be similar to those those between the newly proposed parameters P_1 and P_2, but the residuals present larger values and are dependent on the number of equivalent velocity cycles.

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