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# Relation of Pulse Period with Near-Fault Strong Motion Parameters

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## ABSTRACT

Strong velocity pulses with significant damage potential to structures, attributed to near fault effects, have been identified in many catastrophic seismic events. In an effort to better understand the characteristics and the behavior of such pulses, a statistical analysis of the pulse period in relation with several seismological parameters is performed herein. To this end, a recently proposed method, which can successfully identify the predominant pulse in pulse-like records, is used. The method applies the widely used Mavroeides and Papageorgiou "wavelet" for the mathematical representation of the pulse, the period $T_p$ of which is determined from the peak of the $S_d \times S_v$ product spectrum. The remaining parameters, namely the amplitude $A$, the duration $\gamma$ and the phase shift $v$, are calculated so that the displacement response spectrum of the pulse for 5% damping best fits the corresponding spectrum of the record. In the present paper, a wide set of records from the NGA database that have been characterized as pulse-like is used for a statistical investigation of the relation of the pulse period with three strong-motion parameters, namely: the magnitude of the event; the closest distance to the fault; and the soil type, which is defined by the shear wave velocity. Based on the results, a new empirical relationship for the estimation of the pulse period $T_p$ is proposed.

## Introduction

The increased density of recording stations in the near-fault areas has permitted the collection of ground motions which present characteristics quite different from those of typical far-field records. The main difference concerns the presence of dominant 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, 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, directivity pulses produce a bell shaped amplification of the displacement spectra around the pulse period $T_p$, a feature of special interest in performance based design. For inelastic response, directivity pulses might produce large ductility demands, $\mu$, for periods smaller than the pulse period, quite larger than the corresponding reduction factors, $R$ (Iervolino

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and Cornell, 2008). However, for periods larger than the pulse period, the $\mu/R$ ratio is generally 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, fling step etc. (Rodriguez-Marek 2000, Baker 2007). In this paper, all types of pulse-like records are considered, independently of the cause of their generation.

Velocity pulses inherent in ground motion records are usually visible in the velocity time history. Many researchers have presented various methods to identify their properties and simulate them, mainly using wavelet analysis. Among them, 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. The main parameter, on which the simulation of near-fault ground motions is based, is the pulse period $T_p$ of the significant pulse which is usually distinguishable in the velocity time-history. Several researchers have proposed relations associating linearly the logarithm of $T_p$ with the earthquake magnitude $M_w$ (Somerville 1998, Alavi and Krawinkler 2000, Bray and Rodriguez-Marek 2004, Rupakhety *et al*. 2011).

In this paper, a statistical analysis of the relation of the pulse period with the earthquake magnitude, $M_w$, the closest to the fault distance, *ClD*, and the soil type, which is considered through the shear wave velocity $V_{s,30}$ is performed. *ClD* is defined as the closest distance from the recording site to the ruptured area according to the NGA database. To this end, the pulse period $T_p$ is determined applying the methodology proposed by Mimoglou *et al.* (2014) on a set of 60 records from the NGA strong motion database with peak ground velocity larger than 30 cm/sec and closest distance from the recording site less than 20 km, which have been classified as pulse-like according to a recently proposed method by Kardoutsou *et al*. (2014). The values of the earthquake magnitude, the distance and the shear wave velocity are taken from the NGA database.

## 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, Shahi & Baker 2011).

In the present paper, a recently developed method (Mimoglou *et al.* 2014) is used for the determination of the pulse period $T_p$, according to which 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 was suggested to use the response spectra for 5% damping instead of the ones for zero damping.

## Selection of Pulse-Like Records

A dataset of 60 records from the NGA database, with peak ground velocity larger than 30 cm/sec and closest distance from the recording site less than 20 km, which have been characterised as pulse like according to Kardoutsou *et al.* (2014), is used herein. The aforementioned method is based on the ground motion parameter *CAD* (Cumulative Absolute Displacement, see Taflampas *et al*. 2009), which is defined in analogy with the *CAV* (Cumulative Absolute Velocity) index (EPRI 1991) as the time integral of the absolute ground velocity, i.e.

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

The selected classification 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 ratio between the spectral displacement for zero damping at resonance and *CAD*, which can be expressed as (Mimoglou *et al.* 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, should present a large amplification around the pulse period, $T_p$, and the ratio $S_{d,0}(T_p)/CAD$ should be close to $\pi/4$. In the method proposed by Kardoutsou *et al.* (2014), *CAD* is not calculated for the whole time duration of the ground motion as suggested by Eq. (2), but for a smaller time interval, from $t_{\min}$ to $t_{\max}$, where $t_{\min}$ is the zero crossing time before the first exceedance of the value $0.4PGV$ and $t_{\max}$ is the zero crossing time after 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 spectral displacement for zero damping that corresponds to 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 in Kardoutsou *et al.* (2014), the threshold for this classification is set to 0.65 (somehow lower than $\pi/4$); thus, a record is characterized as pulse-like if $S_{d,0}(T_p)/CAD > 0.65$.

## Statistical Analysis and Results

For the set of the 60 records classified as pulse-like, the pulse period $T_p$ is determined for the normal to the fault component following the above-mentioned procedure and a statistical analysis is performed to examine how $T_p$ is related with the earthquake magnitude, $M_w$, the closest to the fault distance, *ClD*, and the shear wave velocity, $V_{s,30}$. In the examined dataset, the earthquake magnitude $M_w$ ranges from 5.74 to 7.51 and the closest distance to the fault *ClD* takes values from 1 to 20 km.

The relation of $T_p$ with $M_w$ is shown in Fig. 1. It is seen that, as expected, the pulse period generally increases with the earthquake magnitude; however, a linear association of $M_w$ with the logarithm of the predominant pulse period, as suggested by several researchers (Somerville 1998, Alavi and Krawinkler 2000, Bray and Rodriguez-Marek 2004, Rupakhety *et al*. 2011), shows significant discrepancy (solid line in Fig. 1). The large scattering of the results, especially for large magnitudes, implies that the pulse period is affected by other parameters apart from the magnitude. As a first attempt, the effect of the closest distance to the fault, *ClD*, and the shear wave velocity $V_{s,30}$ is examined. An example is shown in Fig. 2 for the records of the Imperial Valley, 1979 earthquake. It is seen that $T_p$ increases with *ClD* and decreases with $V_{s,30}$.

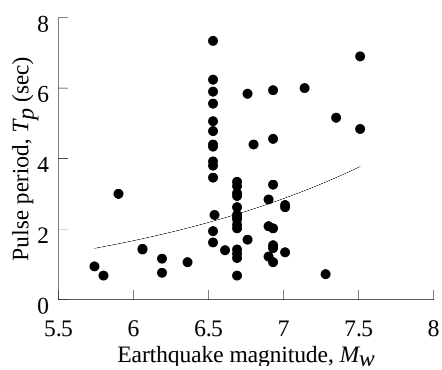


Figure 1: Pulse period $T_p$ vs. earthquake magnitude $M_w$. Solid line corresponds to an exponential fitting curve.

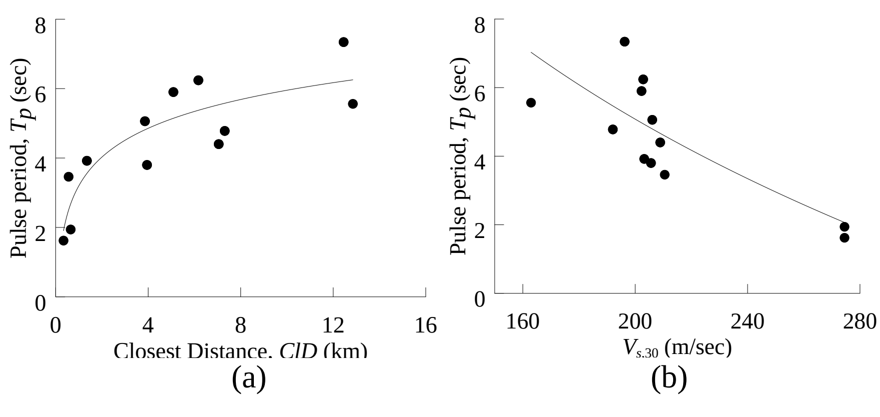


Figure 2: Pulse period $T_p$ (a) vs. *ClD* and (b) vs. $V_{s,30}$ for the Imperial Valley, 1979 earthquake.

Based on the obtained results, a new empirical formula is proposed for the estimation of the pulse period, which, apart from the magnitude, $M_w$, takes under consideration the closest distance, *ClD*, and the shear wave velocity, $V_{s,30}$. This expression is set in the form:

$$T_p = A_1 \mathrm{e}^{M_w + A_2 \cdot V_{s,30}} \left( A_3 + A_4 \ln(ClD) \right) \tag{4}$$

The parameters $A_1$ to $A_4$ are determined from a least-squares regression analysis which results in the following equation:

$$T_p = 0.0022 \cdot \mathrm{e}^{M_w - 0.0001 \cdot V_{s,30}} \left( 1.5 + 0.041 \cdot \ln(ClD) \right) \tag{5}$$

## Evaluation of the Results

In order to evaluate Eq. (5), the plots of the predicted periods $T_p$ versus the *ClD* and the $V_{s,30}$ are shown in Fig. 3 for all the records. In each plot, the pulse period is shown normalized according to Eq. (5) with respect to the other two parameters, apart from the one examined in the specific graph. Thus, $T_{p,n} = T_p / 0.0022 \cdot \mathrm{e}^{M_w - 0.0001 \cdot V_{s,30}}$ and $T_{p,n} = T_p \big/ \left[ 0.0022 \cdot \mathrm{e}^{M_w} \left( 1.5 + 0.041 \cdot \ln(ClD) \right) \right]$ in Figs. 3(a) and 3(b), respectively. Black dots correspond to the calculated values and solid lines to Eq. (5). Similarly, in Fig. 4 the normalized period is shown versus the magnitude $M_w$; in this case, the normalized period was set to $T_{p,n} = T_p \cdot \mathrm{e}^{0.0001 \cdot V_{s,30}} / 0.0022 \cdot \left( 1.5 + 0.041 \cdot \ln(ClD) \right)$.

It is obvious from Figs. 3 and 4 that, although the predicted periods by Eq. (5) are, in general, quite close to the calculated ones, there are significant differences in some cases. Comparison of Fig. 4 with Fig. 1 shows that the proposed formula decreases considerably the scattering of the results, but there are still large discrepancies suggesting that there might be additional parameters affecting the value of $T_p$, as the type of the fault. This is also suggested from Fig. 2, in which the results for the Imperial Valley, 1979 earthquake are shown, where the pulse periods show much smaller scattering as they refer to the specific fault type.

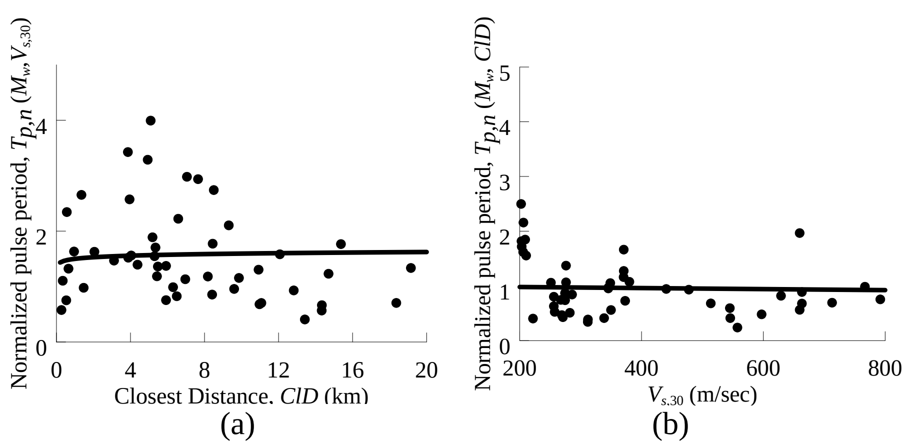


Figure 3: (a) Normalized pulse period, $T_{p,n}$, vs. *ClD* and (b) normalized pulse period, $T_{p,n}$, vs. $V_{s,30}$ for the total set of records. Solid line corresponds to Eq. (5). The pulse period is shown normalized with respect to the other two parameters, apart from the one examined in each graph.

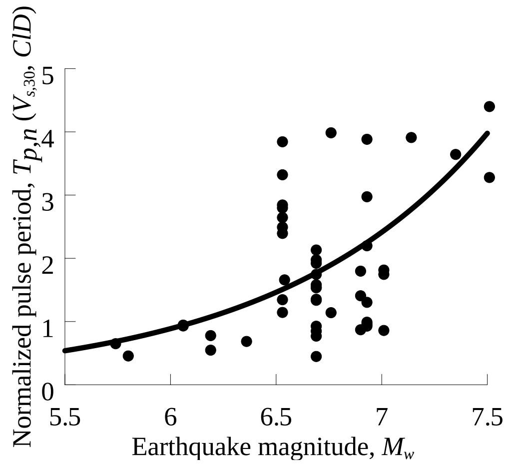


Figure 4: Normalized pulse period, $T_{p,n}$, vs. $M_w$. Solid line corresponds to Eq. (5). The pulse period is shown normalized with respect to the closest distance and the shear wave velocity.

## Comparison with Other Formulas from the Literature

In Fig. 5(a), the proposed equation (5) (dashed lines) is compared with other relations from the literature, namely the expressions proposed by Somerville (1998), Alavi and Krawinkler (2000), Bray and Rodriguez-Marek (2004), Rupakhety *et al.* (2011). Curves are shown for extreme values of the closest distance, namely *ClD* = 1 km and 20 km, and the shear wave velocity, namely $V_{s,30}$ = 200 m/s and 1000 m/s. It is seen that the proposed formula predicts somehow larger values of the pulse period compared with the previous formulas; however, these formulas also show significant discrepancy with the calculated periods, as depicted in Fig. 5(b).

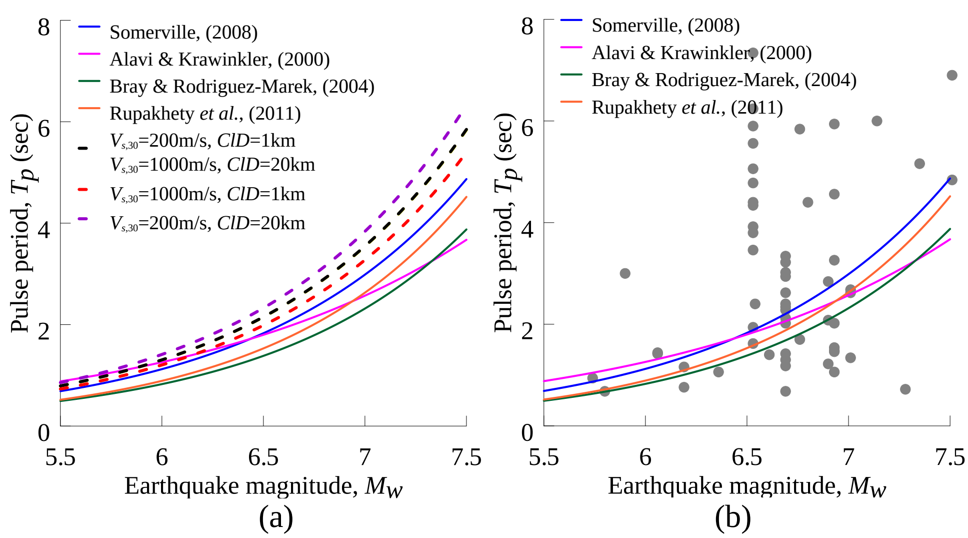


Figure 5: (a) Comparison of Eq, (5) (dashed lines) with other relations by several researchers; (b) comparison of these relations with the calculated values.

## Conclusions

A statistical investigation of the relation of the velocity pulse period of pulse-like records with the earthquake magnitude, the closest distance to the fault and the shear wave velocity of the ground is performed. The pulse periods are calculated applying a recently proposed method, according to which the period $T_p$ is determined from the peak of the $S_d \times S_v$ product spectrum. For a set of 60 records classified as pulse-like, a regression analysis is performed and an empirical formula is established. The results show that the earthquake magnitude combined with the closest distance and the shear wave velocity have significant contribution to the estimation of the pulse period; however, other parameters, not considered in this investigation, as the type of the fault, might be important.

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