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Wavelet-based Analysis for Pulse Period of Earthquake Ground-motions

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A B S T R A C T

Pulse period of earthquake records has been known as a key parameter in seismology and earthquake engineering. This paper presents a detailed characterization of this parameter for a special class of earthquake records called pulse-like ground motions. This type of motion is often resulted from directivity effects and is characterized by a strong pulse in the velocity time history of motion, in normal-fault component. Wavelet analysis was used as a powerful and useful technique in the analysis of non-stationary signals in this study. The period of velocity pulses is basically determined using the pseudo-period of the mother wavelets. The effects of three different mother wavelets on results were investigated and new empirical predictive equations for pulse period have been derived.

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1. INTRODUCTION

Attention to the significant differences of near and far-field ground motion has been raised by various researchers in the past. These differences could be summarized in two main characteristics named “rupture directivity” and “fling step” observed in near-field ground motions. Directivity phenomenon could be demonstrated in the form of forward, backward and neutral effect depending on direction of rupture propagation. In case of forward directivity, the most of seismic energy radiated from the source appears as a distinct strong pulse in the ground motion perpendicular to the fault strike. Much evidence of such effect as a basic attribute of near-field ground motions has been reported in recent destructive earthquakes 1978 Tabas, Iran; 1995 Kobe, Japan; 1999 Chi-Chi, Taiwan; 2003 Bam, Iran and 2009 L’ Aquila, Italy [1-4].

Pulse-like motions can impose considerable seismic demands and consequently severe damage on structures in near-field area. The effects of pulse on engineering structures performance have been pointed out by several researchers [5-11]. The period of pulse in velocity time history was known as an important parameter which controls the performance of structure subjected to pulse-like ground motions. Kalkan and Kunnath demonstrated that the demands of steel-frame buildings with fully rigid connections under pulse-like motions are controlled by the ratio of the period of structure to pulse period (T/T_p) [8]. Recently, Chioccarelli and Iervolino discussed the amplification of elastic and inelastic seismic demands for pulse-like fault-normal records of 2009 L’ Aquila, Italy earthquake versus the (T/T_p) [3]. They also emphasized that modification to inelastic demand should be taken into account properly in seismic design of structures in near-fault area.

Baker has developed an algorithm based on a continuous score called pulse indicator to classify records as pulse and non-pulse ground motions [12]. This method which was adopted in this paper, produced based on continuous wavelet transform (CWT) analysis, is capable to extract strong pulses from a given original ground motion. In this procedure, the period of velocity pulses was simply determined using the wavelet pseudo-period corresponding to the largest CWT coefficient.

In the present paper, a wavelet-based analysis is used to extract the largest pulse from the fault-normal component of the pulse-like motions. The period of velocity pulses as a key parameter is simply determined

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using pseudo-period of the mother wavelets. The efficiency of different types of mother wavelets on estimated pulse period is investigated by applying three different kinds of mother wavelets. It is important to note that these mother wavelets are chosen from both orthogonal and bi-orthogonal wavelet families. Moreover, magnitude scaling of pulse period is discussed and compared with other predictive equations.

2. REVIEW OF WAVELET TRANSFORMS

Complex source mechanisms along with propagation of seismic waves generated during the rupture process cause the non-stationary character of earthquake motions. Fourier and wavelet transforms of signals can be powerful tools for the processing of earthquake signals in the frequency domain. In Fourier transform, the basis function $\exp(-i2\pi ft)$ which is extending from $-\infty$ to $+\infty$ is applied for moving from a time-domain signal into a frequency domain as follow:

$$FT(f) = \int_{-\infty}^{\infty} g(t)\exp(-i2\pi ft)\,dt \tag{1}$$

Unlike the Fourier transform, the wavelet transform basis functions are functions of the same shape that are concentrated in time and frequency. In fact, the wavelet transform as a powerful tool represents a time-domain function by means of a linear combination of basis functions.

The mother wavelet function that is scaled by *a* and translated by *b* is denoted by $\psi_{a,b}(t)$ and given as:

$$\psi_{a,b}(t) = \frac{1}{\sqrt{a}}\psi\left(\frac{t-b}{a}\right) \tag{2}$$

In wavelet transform a set of functions derived by scaling and translation of the one function (mother wavelet, $\psi(\bullet)$) is used to analyze different frequency bands by the following convolution:

$$WT[g;a,b] = \frac{1}{\sqrt{|a|}}\int_{-\infty}^{\infty} g(t)\psi^{*}\left(\frac{t-b}{a}\right)dt \tag{3}$$

where $a \neq 0$ and b are real values called the scale and shift or position parameters, respectively and symbol * denotes complex conjugation. For $a > 1$ there is stretching of $\psi(t)$ along the time axis. Result of the wavelet transform is representing as $WT[g;a,b]$ which is a time-scale map (or Scalogram). The factor $1/\sqrt{|a|}$ is used to normalize the energy to keep the energy at the same level for different values of *a* and *b*. The reconstruction formula of *g*(*t*) is given as:

$$g(t) = \frac{1}{2\pi C_{\psi}}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\frac{1}{a^{2}}WT[g,a,b]\psi\left(\frac{t-b}{a}\right)da\,db \tag{4}$$

$$C_{\psi} = \int_{-\infty}^{\infty}\frac{|\hat{\psi}(\omega)|^{2}}{|\omega|}d\omega \tag{5}$$

where $\hat{\psi}(\omega)$ is the Fourier transform of $\psi(t)$ and the coefficient of C_{ψ} is a constant which depends on the selected mother wavelet. More detailed description about mathematical background of wavelets can be found in text books on the subject [13].

3. HAAR, DB4 AND BIOR 1.3 WAVELETS

Application domain of wavelet transforms in seismology and earthquake engineering is increasing rapidly. In this way, various types of mother wavelets have been considered in literatures which are classified as orthogonal and bi-orthogonal wavelets. Three different mother wavelets named as the Haar, the Daubechies wavelet of order 4 (db4) from orthogonal families and BiorSpline (bior1.3) as a bi-orthogonal wavelet have been chosen herein. Many relevant applications have been reported for these types of wavelets which are summarized briefly in this section of the paper.

The Haar wavelet as a special case of Daubechies wavelet (i.e. db1) is the simplest form of wavelets used in the analysis. This type of mother wavelet has been found appropriate for processing signals that have spiky changes because of its fairly narrow span over which its energy is distributed [14]. Quek et al., have used the Haar mother wavelet for sensitivity analysis of crack detection in beams, showed its superior performance for detection of discrete cracks [15]. Recently, Vassiliou and Makris used this type of mother wavelet to estimate time scales and length scales on pulse-like earthquake acceleration records [16].

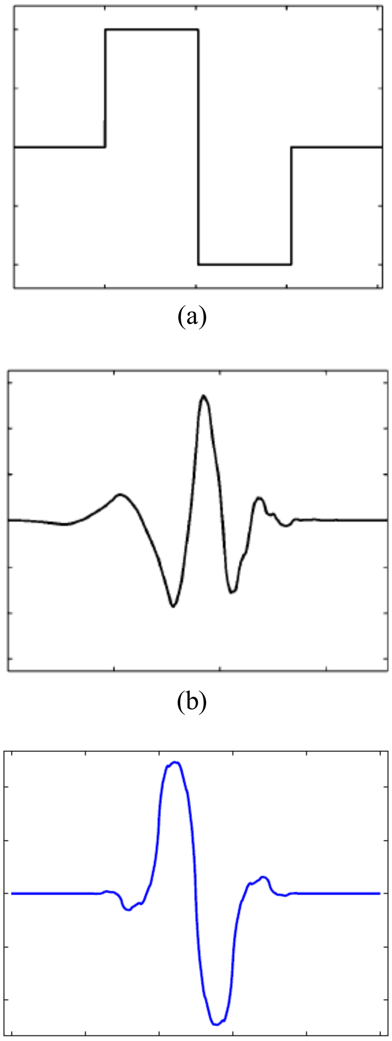
The db4 wavelet as a well-known mother wavelet has a reasonable support with good time-frequency localization property. Increasing the order of the Daubechies wavelet (from 1 in Haar to 4 in db4) gives greater compactness in the frequency domain, but less so in the time-domain [17]. Pan and Lee used db4 wavelet to identify yielding in seismic response of bi-linear structures with single degree of freedom [18]. The Daubechies wavelet of order 4 (db4) has been used by Baker for quantitative classification of near-field ground motions [12]. Application of wavelet analysis in tsunami early warning by using db4 has been pointed out by Lockwood and Kanamori [19]. This type of wavelet has been selected in the work of Ghodrati Amiri and Asadi for processing of ground motion records [20]. Gholizadeh and Samavati employed a combination of a wavelet-based analysis using db4 wavelet with neural networks to implement optimization of structural design for earthquake loading [21]. Mallaioli and Bosi used db4 wavelet for the characterization of forward-directivity pulse-like ground motions on energy basis [22].

The bior1.3 belongs to bi-orthogonal wavelets which are families of compactly supported symmetric wavelets with two scaling functions rather than having one scaling and wavelet function. The symmetry of the filter coefficients in these wavelets is frequently useful as it results in linear phase of the transfer function. Successful use of bior1.3 wavelet in ground motion analysis has been reported in the past by various researchers as Duan et al., and Yaghmaei-Sabegh [23-24]. Chanerley and Alexander applied bior1.3 wavelet at a proper level of decomposition to extract the low frequency fling model in the acceleration time histories [25]. The selected mother wavelets in this paper are illustrated schematically in Figure 1.

4. WAVELET-BASED ANALYSIS OF GROUND MOTIONS

Ground motion characteristics could be demonstrated generally in the form of a scalogram through the wavelet coefficients of continuous wavelet transform. As illustrated in section 2, wavelet coefficients (i.e. the value of $WT[g;a,b]$) depend on the type of mother wavelet used in the procedure and consequently scale-resolution of an arbitrary motion would be developed in different styles. An example of the differences between wavelet scalograms (or time-scale resolutions) obtained by analyzing an earthquake time series with different mother wavelets (Haar, db4 and bior 1.3 wavelets) is presented in Figure 2. In this figure which describes the signal energy on a time-scale domain, the analyzed signal in the top plot is a ground motion record of Loma Preita 1989 event obtained at Oakland - Outer Harbor Wharf station. The horizontal axis of Figure 2 shows the time (or the translation parameter b) versus the frequency (or the scaling parameter a) in vertical axis. The brighter portions in this figure point out higher absolute values of the wavelet coefficients. The position of frequencies with the largest magnitude at any given time is also clear in this figure. It is worthy of note that the high frequencies appear at the bottom of the scalogram at low scale values.

In 2007, Baker proposed a new method in which the large pulse of ground motions is extracted based on continuous wavelet transform. The Daubechies wavelet of order 4 (db4) has been used by Baker as a well-known mother wavelet for this purpose. The Baker's method was adopted in this paper to explore the effect of different mother wavelet on determining the velocity pulse period. The dataset of recorded accelerograms employed in this study comprises 91 large velocity pulses in the fault-normal components of strong ground motion recordings of the Next Generation Attenuation (NGA) project library (www.peer.berkeley.edu), classified by Baker as pulse-like ground motions [12].

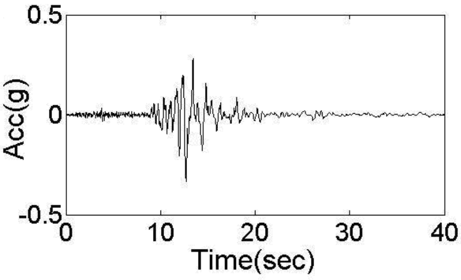


(a)

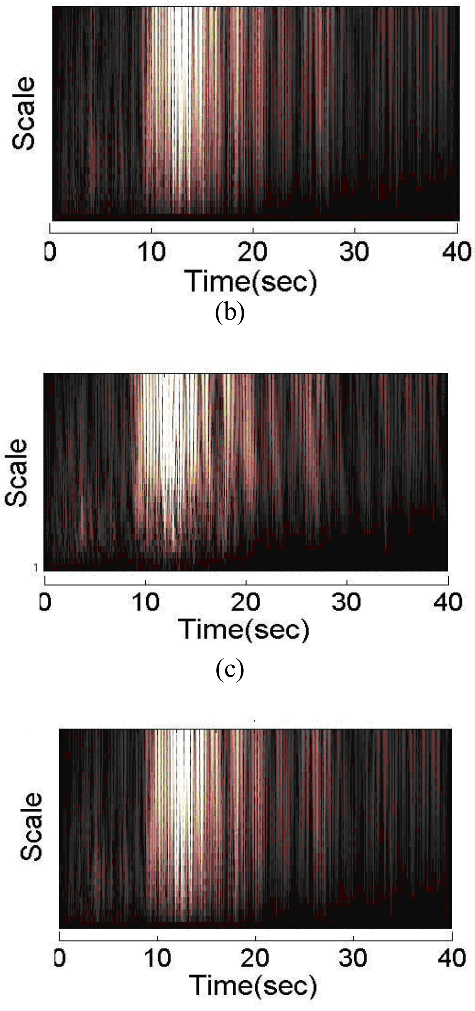
(b)

(c)

Figure 1. Schematic representation of a) Haar, b) db4 and c) bior1.3 wavelet



(a)



(b)

(c)

(d)

Figure 2. (a) Acceleration time history along with continuous wavelet analysis (time-scale plane) of the Loma Prieta event recorded at Oakland-Outer Harbor Wharf station based on b) Haar c) db4 and d) bior1.3 wavelets

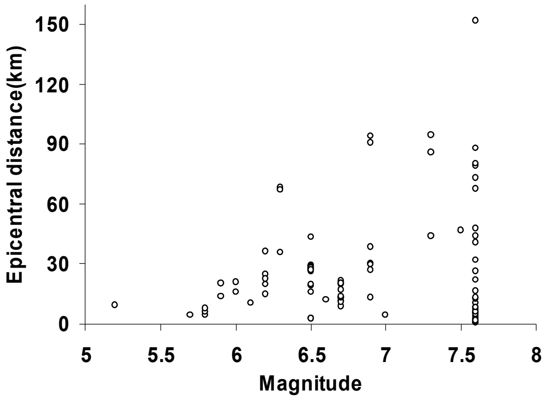


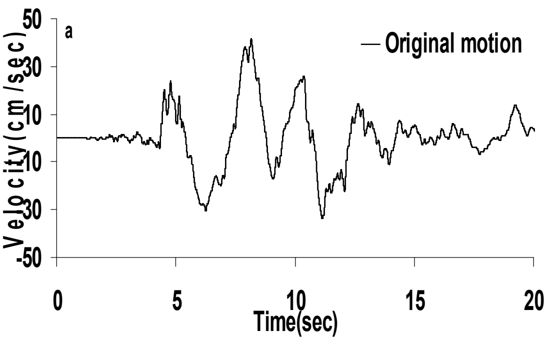
Figure 3. Scatter plot of magnitude and epicenteral distance parameters

In addition, two Tabas and Bam records which were obtained, respectively, from the two destructive earthquakes of Tabas 1978 and Bam 2003 have been added to database. These records were detected as pulse-like near-fault ground motions in Iran with pulse indicator close to 1 [24].

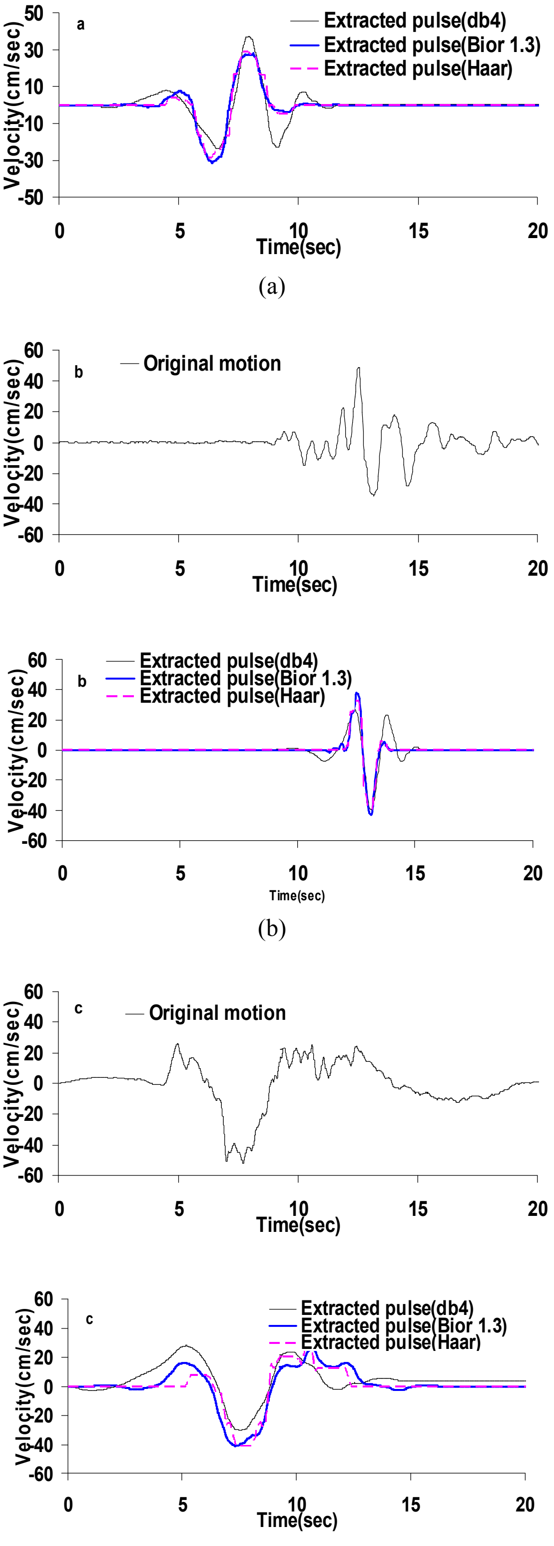
Figure 3 shows the scatter plot of magnitude versus the epicentral distance in the database which includes records from destructive earthquakes such as; Imperial Valley (1979), Loma Prieta (1989), Northridge, United States (1994), Kobe, Japan (1995), Chi-Chi, Taiwan (1999) and Kocaeli, Turkey (1999). Examples of the velocity time history of original ground motions along with the associated extracted pulses are shown in Figure 4 for events 1980, Irpinia (Italy); 1989, Loma Prieta (USA) and 1999 and Kocaeli (Turkey), recorded respectively at Sturno, Oakland-Outer Harbor Wharf, and Gebze stations. To visualize the effect of different mother wavelets on the extracted pulse features, the results have been presented for three different mother wavelets db4, Haar (from orthogonal wavelet families) and bior1.3 wavelets which belong to bi-orthogonal wavelet basis function. As shown in Figure 4, the pulses extracted form each pulse-like motion depend on the type of mother wavelet used in pulse extraction procedure.

5. MAGNITUDE SCALING OF PULSE PERIODS

Several definitions of the pulse period were proposed and widely used in the past; however there is not a unique technique in the scientific literature to define the period of the velocity pulse. The representation of pulse period corresponding to the period of pulse with largest amplitude (T_V) or global peak in the velocity response spectrum of ground motion at 5% damping ratio (T_{V-P}) was adopted commonly by various researchers [26-27].



(a)



(a)

(b)

(c)

Figure 4. Velocity time history of original ground motions along with the associated extracted pulses for a) 1980, Irpinia (Italy) b) 1989, Loma Prieta (USA) and c) 1999, Kocaeli (Turkey) events, recorded respectively at Sturno, Oakland-Outer Harbor Wharf, and Gebze stations

In other case, T_V could be defined by applying the zero crossing time or the time at which velocity is equal to 10% of the peak velocity for this pulse. For a simple velocity time-history defined by a one-cycle sine pulse, T_{V-P} is close to the value of T_V while for events with more complex velocity time histories T_{V-P} could be considerably lower than T_V. The weighted average period is another alternative for defining the pulse period. It is defined as the sum of the periods of each half-cycle of motion weighted by the pulse amplitude and divided by the number of half-cycles of motion [28]. Mavroeidis and Papageorgiou determined pulse period so that the velocity response spectra of their equivalent synthetic and observed motions show their maximum value at approximately the same period [26]. The energy-based definition was adopted by Mallaioli and Bosi as the period matching to the peak value in elastic input energy spectrum with 5% damping ratio [22].

Relationship between pulse period of pulse-like ground motions and earthquake magnitude has been pointed out by numerous researchers such as Somerville [29-30], Somerville et al. [31], Alavi and Krawinkler [32], Mavroeidis, and Papageorgiou [26] and Bray and Rodriguez-Marek [27]. These relationships related the magnitude of earthquake linearly to the logarithm of pulse period as determined based on different definitions. In 2007, Baker derived a new relationship in which the velocity pulse has been deliberated based on a wavelet based analysis [12]. Table 1 presents a summary of some of these relationships along with a new one proposed by Mena and Mai [33].

TABLE 1. Relationships between pulse period and magnitude of earthquake in literature

No	Relationships	Reference
1	$\log(T) = -2.2 + 0.4M_w$	[26]
2	$\log(T) = -3.17 + 0.5M_w$ rock sites $\log(T) = -2.02 + 0.34M_w$ soil sites	[30]
3	$\ln(T) = -6.37 + 1.03M_w$	[27]
4	$\ln(T) = -5.78 + 1.02M_w$	[12]
5	$\ln(T) = -6.28 + 1.07M_w$	[23]

The velocity pulse period in wavelet-based analysis results from pseudo-frequency of wavelet ($\bar{\xi}_j$) as follows:

$$\bar{\xi}_j = \frac{\xi_\psi}{j\Delta t} \tag{6}$$

where ξ_ψ is the central frequency of wavelet ψ in Hz, j is the scale of wavelet and Δt is sampling period. Accordingly, pseudo-period of the largest wavelet coefficient is defined as the inverse of the pseudo-frequency.

Estimated pulse period based on this procedure depends on the type of selected mother wavelet used in the analysis. It is well-known that, there is no general systematic method for choosing the mother wavelet, and generally it depends on the type of analysis and the characteristic of function to be analyzed. To explore the effect of mother wavelet in prediction of pulse period which is the main purpose of this article, results of pulse period predictions based on different mother wavelets (Haar, db4 and bior1.3) for the records of Irpinia 1980, Loma Preita 1989, Landers 1992, Kobe 1995 and Kocaeli 1999 have been summarized in Table 2. This table shows clearly the difference between the results determined based on different mother wavelets. Among the three selected mother wavelets, a lower value of period for velocity pulse can be achieved while the Haar mother wavelet is applied. A plot of pulse-period values vs. magnitude achieved from the wavelet analysis is shown in Figure 5 for the 93 pulse-like ground motions used in this study. Corresponding to each mother wavelet, three predictive relationships between pulse periods T_P and earthquake magnitude (M) (Equations (7)-(9) respectively for db4, bior 1.3 and Haar mother wavelets) were obtained and superimposed in this figure.

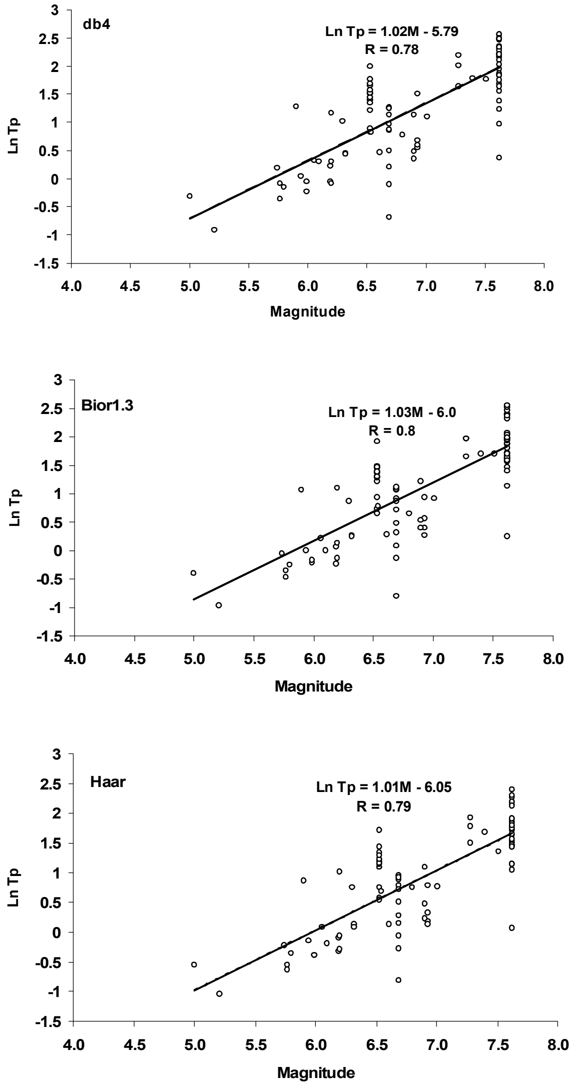


Figure 5. Pulse periods versus magnitude based on three different mother wavelets

$$\ln(T_P) = -5.79 + 1.02M_w \tag{7}$$

$$\ln(T_P) = -6.00 + 1.03M_w \tag{8}$$

$$\ln(T_P) = -6.05 + 1.01M_w \tag{9}$$

Correlation coefficients (R^2) calculated for the above equations are 0.78, 0.80 and 0.79, respectively which are very close to each other.

A plot of Equations (7)-(9) has been presented in Figure 6 along with the predictive relationships developed by Mavroeidis and Papageorgiou, Bray and Rodriguez-Marek and Mena and Mai [26-27, 33]. Also, pulse period corresponding to the peak of pseudo velocity response spectrum (T_{V-P}) was derived as $\ln(T_{V-P}) = -5.43 + 0.91M_w$ revealed in this figure.

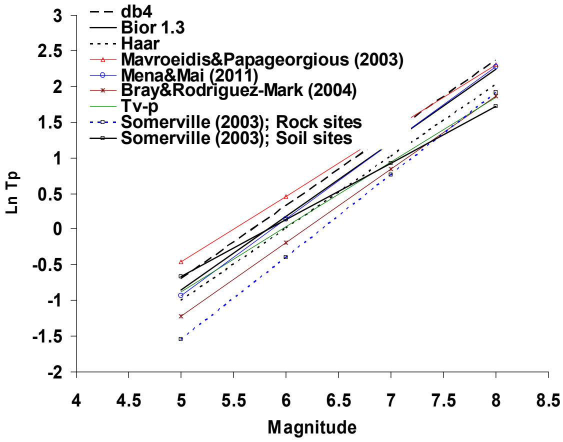


Figure 6. Proposed relationships between T_p and M based on different mother wavelets

TABLE 2. Estimation of the value of pulse period using three different mother wavelets; db4, bior 1.3 and Haar

Event	Station	Mw	Tp (db4)	Tp (bior1.3)	Tp (Haar)
Irpinia, Italy-01 (1980)	Sturno	6.9	3.1	3.4	3.0
Loma Prieta (1989)	Alameda Naval Air Stn Hanger	6.9	2.0	1.8	1.4
Loma Prieta (1989)	Gilroy Array #2	6.9	1.7	1.5	1.2
Loma Prieta (1989)	Oakland - Outer Harbor Wharf	6.9	1.8	1.3	1.1
Loma Prieta (1989)	Saratoga - Aloha Ave	6.9	4.5	2.6	2.2
Landers (1992)	Barstow	7.3	8.9	7.2	5.9
Landers (1992)	Lucerne	7.3	5.1	5.2	4.5
Landers (1992)	Yermo Fire Station	7.3	7.5	7.2	6.9
Kobe, Japan (1995)	Takarazuka	6.9	1.4	1.7	1.6
Kobe, Japan (1995)	Takatori	6.9	1.6	1.5	1.3
Kocaeli, Turkey (1999)	Gebze	7.5	5.9	5.5	3.9

Several important remarks can be made from Figure 6. Amongst the three wavelet-based models represented by Equations (7)-(9), the lowest values of pulse period were predicted by the model where Haar mother wavelet was used. All of wavelet-based pulse periods were predicted larger than the value of the velocity-spectral based models which is in agreement with the finding of Bray and Rodriguez-Marek [27] and Baker [12]. The periods obtained from the wavelet-based analysis by bior1.3 mother wavelet is very close to the period values predicted by Mena and Mai [33]. It is worth noting that the updated model of Mena and Mai (2011) determined the pulse period based on comparison of the period of the best fitting sine wave to the extracted pulse with the zero-crossing time period [33]. Among all the predictive relationships used in comparative analysis, the model of Bray and Rodriguez-Marek [27] which was derived based on largest amplitude of velocity of around 50 near-fault ground motion records estimates the lowest values for pulse period.

The results in this section showed that derived pulse period of a pulse-like motion and consequently magnitude scaling of this parameter depends on type of mother wavelet chosen in the procedure. A possible way to resolve this problem is adopting herein as the average value of pulse periods achieved based on different mother wavelets. As a result, the following predictive equation for magnitude scaling of pulse period is resulted:

$$\ln(T_P) = -5.95 + 1.02M_w \tag{10}$$

It is noted that, the predictive values by the new equation are very close to those of Equation (8) which have been derived based on bior1.3 mother wavelet.

Haar is the simplest wavelet which could provide a overall behavior from the extracted pulses; however it is not able to exactly simulate the near-fault record for all the cases. Therefore, the lower values of pulse period are predicted when Haar is applied in the analysis. In other side and as shown in Figure 6, the higher values of pulse period are expected for the db4 mother wavelet. As an appropriate alternative, T_p prediction by bior 1.3 is close to the average of three selected mother wavelets in the analysis.

6. CONCLUDING REMARKS

The results of present work highlighted the application of wavelet-based analysis for characterization of special type of ground motions named “pulse-like motions”. The procedure that implemented in this paper used wavelet-based signal processing simply to identify and extract the largest velocity pulse from an earthquake ground-motion record. The period of an extracted velocity pulse, a parameter of interest to both engineers and seismologist, was easily estimated. As a fully automated alternative, the procedure is straightforward and computationally inexpensive to compute a pulse period as part of time-frequency analysis of ground motions.

The paper compared the use of various types of mother wavelets on the analysis of pulse-like motions. The framework of this study was illustrated using three different mother wavelets; db4, bior 1.3 and Haar. A wavelet-based analysis was used to derive empirical relationships that relate the pulse period to the moment magnitude. The analysis showed that the results of this method would be affected by the mother wavelet employed and the success of the wavelet transform in more rational estimation of pulse period depends on the type of mother wavelet. In other words, great care is needed when using a single mother wavelet in the analysis procedure and it should be selected based on the nature of the ground motion that is not possible in all cases. As a simple way out, a new predictive relationship which considered the average value of pulse periods based on different mother wavelets has been presented in this paper.

7. ACKNOWLEDGMENT

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Wavelet-based Analysis for Pulse Period of Earthquake Ground-motions

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چکیده

پریود پالس پارامتری مهم در زلزله شناسی و مهندسی زلزله به شمار می رود. این مقاله به بررسی مشحصه های کامل این پارامتر درگروه خاصی از زلزله ها بنام حرکت های پالس-گونه می پردازد. این حرکت ها معمولا به دلیل اثرات جهت داری در حوزه نزدیک گسل و در راستای عمود بر گسل بوجود می آید. در این مطالعه تحلیل موجک ها به عنوان ابزاری قوی در تحلیل سیگنالهای نامانا مورد استفاده قرار می گیرد. پریود پالس با استفاده از مفهوم شبه پریود متناظر با موجک مادر محاسبه می شود. اثرات سه موجک مادر مختلف در تخمین پریود پالس بررسی و در انتها رابطه تجربی جدیدی ارائه خواهد شد.

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