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A New Pulse Indicator for the Classification of Ground Motions

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Abstract Pulse-like seismic records constitute a special category of ground motions, because they are capable of causing significant damage to several structures. In this article, a new pulse indicator (PI) for the characterization of seismic motions as pulse-like or non-pulse-like is proposed, which is set equal to the cross-correlation factor of the significant pulse and the original record. It is suggested that records for which PI is greater than 0.65 are characterized as pulse-like, whereas records with PI less than 0.55 are characterized as non-pulse-like. The method is applied to a total of 221 records that have been characterized in the literature as pulse-like, non-pulse-like, or ambiguous, and the comparison of the new PI with previously proposed indicators is performed. It is also shown that the proposed PI is related to the inelastic response of structures, because records characterized as pulse-like produce, in general, inelastic displacements larger than the elastic ones. In the presented examples, the Mavroeidis and Papageorgiou wavelet is used for the mathematical representation of the predominant pulse inherent in a record; however, other types of wavelets could also be used.

Electronic Supplement: Tables of classification of considered records and proposed pulse indicator (PI) index for records characterized as pulse-like.

Introduction

The increased density of recording stations in the near-fault areas has permitted the collection of near-field ground motions, which present characteristics quite different from those of typical far-field 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. More specifically, the wavefront arrives as a large pulse of motion in the beginning of the record and is polarized in the strike normal direction (Somerville *et al.*, 1997). Based on that observation, many researchers used the fault-normal direction, as that of the strongest component of a record, to study the phenomenon of directivity (Mavroeidis and Papageorgiou, 2003; Mavroeidis *et al.*, 2004; Baker, 2007; Iervolino and Cornell, 2008; Shahi and Baker, 2011; Lu and Panagiotou, 2014).

The classification of records as pulse-like or non-pulse-like is of special interest in the field of engineering seismology and earthquake engineering due to the effect of directivity pulses on the elastic and inelastic response spectra (Bertero *et al.*, 1978; Somerville, *et al.*, 1997; Somerville, 1998, 2003; Alavi and Krawinkler, 2000, 2001, 2004; Luco and Cornell, 2007; Zhai *et al.*, 2007; Sehhati *et al.*, 2011; Zamora and Riddell, 2011; Champion and Liel, 2012). Regarding the elastic response, directivity pulses produce a bell-shaped amplification of the response spectra around the pulse period T_p. For inelastic response, directivity pulses might produce large ductility demands μ for structures with a predominant period close to one half of the pulse period, quite larger than the value of the corresponding reduction factor R, which would be expected according to the equal displacement rule (Iervolino and Cornell, 2008). However, for structures with a period equal to or larger than the pulse period, the μ/R ratio is generally close to unity, and the equal displacement assumption holds.

Velocity pulses inherent in ground-motion records are usually visible in the velocity time history. Many researchers have presented various methods to simulate them, mainly using wavelet analysis. Among them, Mavroeidis and Papageorgiou (2003) proposed a very efficient model for the mathematical representation of the pulse, based on the amplitude, the period, the duration, and the phase shift.

Furthermore, Baker (2007) developed a new method for detecting pulses in ground motions. The procedure uses wavelet-based signal processing to identify and extract the largest velocity pulse from a ground motion by applying two main criteria: (1) that the pulse arrives early in the ground motion and (2) that the absolute amplitude of the velocity pulse is large. The method leads to the introduction of a pulse indicator (PI), which can be used for the quantitative classification of near-fault ground motions as pulse-like or non-pulse-like.

A different method for the identification of pulse-like ground motions was introduced by Zhai *et al.* (2013), based on energy considerations. Specifically, ground motions for which dominant velocity pulse holds an energy value greater than a specific amount of the total energy are classified as pulse-like. Compared with Baker's results, significant differences are observed in the results obtained with the two methodologies.

Another method based on the energy content of a record for the classification of pulse-like records was proposed by Chang *et al.* (2016). According to this method, the pulse amplitude is determined from the amplitude of the half-cycle pulse having the largest seismic energy, and the PI proposed is defined as the ratio of the energy contained in the predominant pulse to the total seismic energy of the ground motion.

In the present article, the efficiency of a new PI, specifically the cross correlation of the predominant pulse and the original record, is examined. For the mathematical representation of the predominant pulse, the Mavroeidis and Papageorgiou wavelet is applied; however, other wavelets could also be used. The new PI is compared with the classification of Baker (2007) for 221 records with peak ground velocity (PGV) > 30 cm/s, showing, in general, good agreement. Only in a few cases do the new PI contradict Baker's classification.

Determination of the Predominant Pulse

For the classification of records as pulse-like or non-pulse-like, the mathematical representation of the significant pulse of the velocity time history is required. Such models of the predominant pulse of a seismic record have been proposed by several researchers; the most commonly used are presented in the following.

A wavelet-based signal processing was proposed by Baker (2007). The signal is decomposed into wavelets that are localized in time and represent a narrow range of frequencies. For the decomposition of the signal, the Daubechies wavelet of order 4 is used, and the predominant pulse is assigned to the wavelet with the largest coefficient. For the period of the pulse, the pseudoperiod of the extracted wavelet is used, defined as the period associated with the maximum Fourier amplitude of the wavelet.

A different approach was proposed by Zhai *et al.* (2013). In this case, the identification of the velocity pulse is realized by matching the potential pulse with a specified model proposed by Dickinson and Gavin (2011). The model has five parameters: peak pulse velocity V_p, pulse period T_p, number of cycles in the pulse N_c, phase of the pulse φ, and location of the pulse T_{pk}. V_p is set equal to PGV, and thus T_{pk} is determined accordingly. Zhai *et al.* (2013) consider one-cycle pulse, therefore, $N_c = 1$ and $\varphi = 0$. The pulse period is determined by the so-called peak point method; the pulse period is set equal to the one-cycle time interval, containing the PGV, between two consecutive peaks or troughs, depending on whether the PGV has a negative or a positive sign.

In the present article, the predominant pulse is determined by applying the recently developed method by Mimoglou *et al.* (2014), in which the Mavroeidis and Papageorgiou (2003; hereafter, M&P) wavelet is adopted for the mathematical representation of the pulse. Four parameters are used to define the pulse: the period T_p; its amplitude A; its duration γ, which measures the number of the oscillations; and the phase shift ν.

As far as the pulse period T_p is concerned, as a common practice it is determined from the peak of the pseudovelocity response spectrum for 5% damping, which has been suggested by several researchers (Somerville, 1998; Alavi and Krawinkler, 2000; Rupakhety *et al.*, 2011). However, the accuracy of this definition has been questioned by other researchers (Rodriguez-Marek, 2000; Baker, 2007). In this article, the pulse period T_p is determined from the peak of the product spectrum $S_d \times S_v$, in which 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, because 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 should 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. In the proposed method, however, it was suggested to use the response spectra for 5% damping instead of the ones for zero damping. It should be noted that the $S_d \times S_v$ method was applied to all 91 pulse-like records of Baker (2007) with excellent results, which are presented in Mimoglou *et al.* (2014).

For the determination of the wavelet's amplitude A, the following equation is used:

$$A = \frac{4\xi \mathrm{PS}_{v,\xi}(T_p)}{(1 - e^{-2\pi\gamma\xi}) \times [1 + (\gamma - 1)\xi]} \qquad (1)$$

(Mimoglou *et al.*, 2014), in which $\mathrm{PS}_{v,\xi}(T_p)$ is the value of the pseudovelocity response spectrum of the ground motion for period T_p and damping $\xi = 0.05$, and γ is the duration, which, however, is not known. For this reason, all the values of γ in a selected range of variation are examined (e.g., up to $\gamma_{\max} = 5$). From this set of pairs (A, γ), the ones that lead to amplitudes of the wavelet's acceleration, velocity, or displacement larger than the corresponding peak values of the ground motion, peak ground acceleration, PGV, and peak ground displacement, respectively, are rejected. For the remaining pairs of (A, γ), and for all values of the phase ν in the range between 0° and 360°, the corresponding wavelets

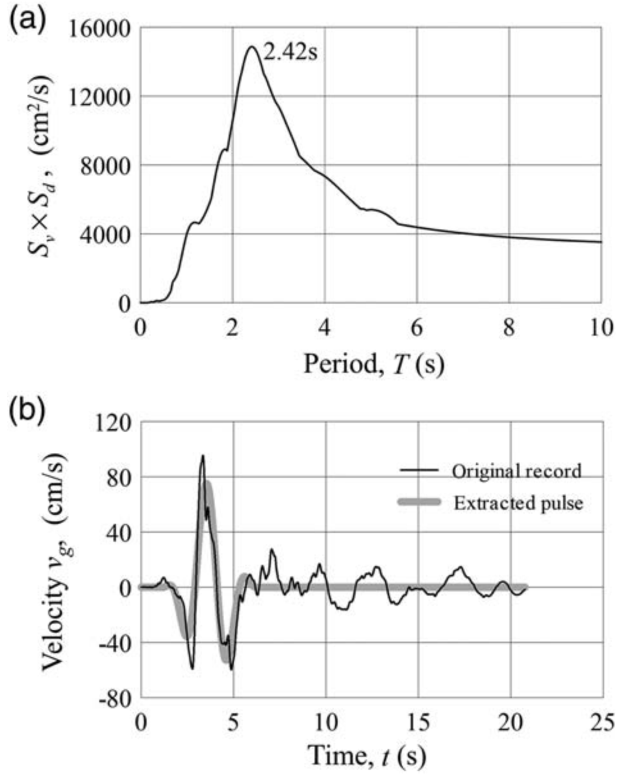

Figure 1. Erzincan record (Erzican, Turkey, 1992 earthquake). (a) $S_d \times S_v$ product spectra for 5% damping and (b) time history of the ground velocity and the calculated predominant pulse.

are calculated, and the wavelet with the largest cross correlation with the original ground motion is selected.

As an example, let us consider the normal-to-the-fault component of the ground motion recorded at Erzincan during the Erzican, Turkey, 1992 earthquake. Application of the Mimoglou *et al.* (2014) method results in $T_p = 2.40$ s (Fig. 1a), a value close to the period of 2.65 s proposed by Baker (2007). In Figure 1b, the pulse determined with the Mimoglou *et al.* method is compared with the time history of the ground velocity, and it is seen that it models well the predominant pulse inherent in the record.

Previously Proposed Pulse Indicators

Up to now, the classification of ground motions as pulse-like or non-pulse-like has been based on the assumption that the energy of a pulse-like ground motion is mostly concentrated in the duration of the pulse (Baker 2007). This also implies that the induced structural deformation dissipates energy in a single or in a few plastic cycles.

Various criteria have been proposed by different researchers regarding this classification. Baker (2007) proposed a PI which takes into account the ratio of the PGV of the residual record, that is, the time history that is calculated by extracting the velocity pulse from the original ground motion, to the PGV of the original record as well as the ratio of the energies of the residual and the original records. These variables are referred to as PGV ratio and Energy ratio, respectively. For the latter, the energy is calculated from the integral of the square of the ground velocity.

The PI proposed by Baker (2007) is given by the following equation:

$$\mathrm{PI} = \frac{1}{1 + e^{-23.3+14.6(\mathrm{PGV\ ratio})+20.5(\mathrm{Energy\ ratio})}}, \tag{2}$$

and takes values between 0 and 1: If PI is larger than 0.85, the record is characterized as pulse-like; if PI is less than 0.15, the record is considered as non-pulse-like; for intermediate values the record is classified as ambiguous. In addition to the above criterion, records that should be classified as pulse-like based on the PI index, but contain late arriving pulses, are finally considered as non-pulse-like.

A similar indicator was proposed by Zhai *et al.* (2013), based on the ratio between the energy contained in the velocity pulse and the total energy of the record. The pulse is calculated according to the model proposed by Dickinson and Gavin (2011) as mentioned above. To this end, the relative cumulative energy $E(t)$ of a ground motion at time t is defined as

$$E(t) = \frac{\int_0^t v^2(t)dt}{\int_0^\infty v^2(t)dt}, \tag{3}$$

in which $v(t)$ represents the velocity time series. The energy E_p contained within a velocity pulse is determined by

$$E_p = E(t_e) - E(t_s), \tag{4}$$

in which t_s and t_e denote the starting and the ending time points of the pulse, respectively. The relative pulse energy E_p is used as the PI. If E_p is larger than 0.3, the record is classified as pulse-like. A possible handicap of this method is that it takes into account only one cycle of the velocity pulse, whereas the number of cycles can be larger.

Another method, also based on the energy content of the record, was proposed by Chang *et al.* (2016), as an improvement of the method by Zhai *et al.* (2013). According to this method, the amplitude of the pulse and its location in the time history of the record are determined by the amplitude of the half-cycle pulse having the largest seismic energy. The proposed PI is defined as the ratio of the energy contained in the predominant pulse to the total seismic energy. If the value of the aforementioned ratio is larger than 0.34, the record is considered as pulse-like. The mathematical representation of the velocity pulse used and the way the energy is computed are the same as in Zhai *et al.* (2013).

New Proposal for the Pulse Indicator

As mentioned above, in the Mimoglou *et al.* (2014) method, the predominant pulse is chosen from the set of all eligible pulses based on the criterion of the largest cross correlation with the original ground motion, because the significant pulse inherent in a ground motion should produce a large cross-correlation factor. This concept is extended here to define a new PI for the characterization of a record as pulse-like or non-pulse-like, based on the factor of the cross correlation r, namely setting PI $= r$.

Remember that the cross-correlation operation between two functions f and g with a time delay t_d is defined by

$$(f * g)(t_d) = \int_{-\infty}^{\infty} f^*(t) \times g(t + t_d)dt, \qquad (5)$$

in which f^* is the complex conjugate of f. The cross-correlation factor r is defined by

$$r = \frac{\sum_i (f(t_i) - \tilde{f}) \times (g(t_i - t_d) - \tilde{g})}{\sqrt{[\sum_i (f(t_i) - \tilde{f})^2] \times [\sum_i (g(t_i - t_d) - \tilde{g})^2]}} \qquad (6)$$

with $\tilde{f}$ and $\tilde{g}$ being the mean values of the functions f and g, respectively.

In our case, the cross-correlation factor r is calculated for the velocity time history of the original record $v_g(t)$ and the velocity time history of the pulse $v_p(t)$, and for time delay t_d equal to the time at which the pulse starts. The cross-correlation factor considered is the maximum between the ground velocity time history and the simulated pulses for all possible time lags. Actually, the procedure used consists of swiping the simulated pulse across the ground velocity time history from the start to the end of its duration, and the point at which the cross correlation of the pulse and the ground velocity present its maximum value defines the position of the pulse in the time history of the ground motion. Then, setting PI $= r$, two thresholds have to be defined, namely $\mathrm{PI}_{cr,\max}$ and $\mathrm{PI}_{cr,\min}$, such that, if PI is larger than $\mathrm{PI}_{cr,\max}$ the record is characterized as pulse-like, whereas if PI is smaller than $\mathrm{PI}_{cr,\min}$ it is characterized as non-pulse-like. To define the appropriate values of $\mathrm{PI}_{cr,\max}$ and $\mathrm{PI}_{cr,\min}$, a calibration of the method is performed in the ensuing based mainly on the characterization made by Baker (2007) for 221 records, and the following values are suggested: $\mathrm{PI}_{cr,\max} = 0.65$ and $\mathrm{PI}_{cr,\min} = 0.55$. Therefore, records with PI > 0.65 are characterized as pulse-like, those with PI < 0.55 are characterized as non-pulse-like, and records with PI values among 0.55 and 0.65 are characterized as ambiguous. As shown in the Evaluation and Verification of the Proposed Pulse Indicator section, the proposed classification is also related to the inelastic response of single-degree-of-freedom (SDOF) structures.

It should be pointed out that, although the majority of pulse-like records can be attributed to near-fault effects (directivity pulses), significant pulses may be produced from other reasons as well, such as basin effects, soil conditions, deep rupture, fling step, and so on (Rodriguez-Marek, 2000; Baker, 2007). In this sense, Baker (2007) considers that records having significant pulse-like features, which, however, are likely caused by effects other than directivity, should not be classified as pulse-like from a strictly seismological point of view. For this reason, he classified records with late-arriving pulses as non-pulse-like, even if they possess a large PI. In this article, emphasis is given to the structural engineering viewpoint, according to which the effect of a strong pulse inherent in the ground motion on the elastic and the inelastic response of the structures is indifferent to the cause of the pulse generation, or to whether the pulse is late arriving or not. For this reason, the Baker's criterion of late-arriving pulses is not adopted, and all records with PI $> \mathrm{PI}_{cr,\max}$ are considered as pulse-like.

The proposed new PI can be applied to any record for which a mathematical expression for the predominant pulse is known. Any appropriate form of wavelet can be used for the mathematical expression of the predominant pulse. As mentioned above, in the analyses presented herein, the M&P wavelet is used, as determined from the application of the Mimoglou *et al.* (2014) methodology. This methodology produces a predominant pulse for any record, no matter whether it is pulse-like or not.

Evaluation and Verification of the Proposed Pulse Indicator

The proposed method was applied to a total of 221 records from the Pacific Earthquake Engineering Research Center–Next Generation Attenuation (PEER–NGA) strong-motion database with PGV > 30 cm/s. The details of the considered records, as given in the NGA database, are shown in Ⓔ Table S1 of the electronic supplement to this article, together with the PI values and the related classification according to the proposed method and Baker (2007). In both cases, the PI values correspond to the normal-to-the-fault direction of each ground motion, as given in the electronic supplement to Baker (2007; see Data and Resources). The results of the application of the proposed PI are presented in Figure 2 and can be summarized as follows: 132 records are characterized as pulse-like (points above top solid line), 48 as non-pulse-like (points below bottom solid line), and 41 as ambiguous (points between top and bottom solid lines).

To compare this classification with Baker's classification, different symbols were used in Figure 2, depending on the corresponding Baker's PI value, as given in the electronic supplement to Baker (2007) (also shown in Ⓔ Table S1). Specifically, 108 records possess $\mathrm{PI}_{\mathrm{Baker}}$ larger than 0.85, thus these records should be characterized as pulse-like according to Baker's criterion; however, only 91 of them (denoted by solid black circles) are finally classified as pulse-like in Baker (2007), whereas the remaining 17 (denoted by open circles) were excluded, as they contained late-arriving pulses. Non-pulse-like records, with $\mathrm{PI}_{\mathrm{Baker}}$ less than 0.15, are denoted with gray crosses and ambiguous ones, for which $0.15 < \mathrm{PI}_{\mathrm{Baker}} < 0.85$, are denoted with diamonds. Remember that, in the present article, records with late arriving pulses are not excluded, thus all points denoted with either solid or open circles are considered as pulse-like based on Baker's PI.

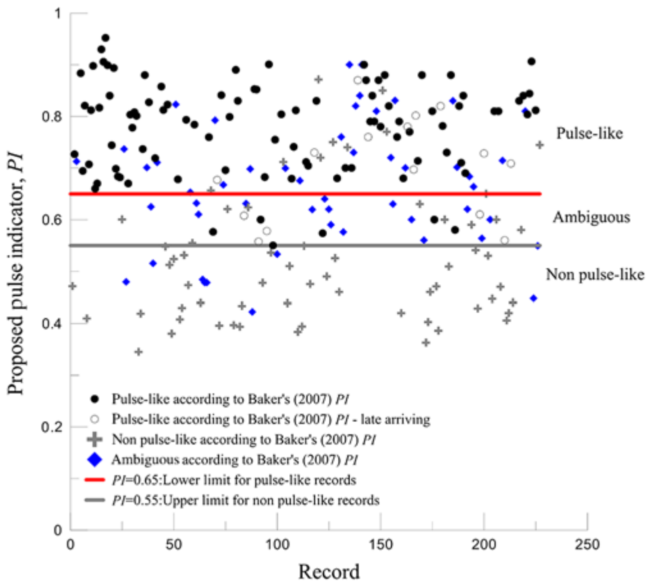

Figure 2. Proposed pulse indicator (PI) of the considered records and comparison with the classification of Baker (2007). The proposed thresholds of $\mathrm{PI}_{cr,\max} = 0.65$ and $\mathrm{PI}_{cr,\min} = 0.55$ are shown. The color version of this figure is available only in the electronic edition.

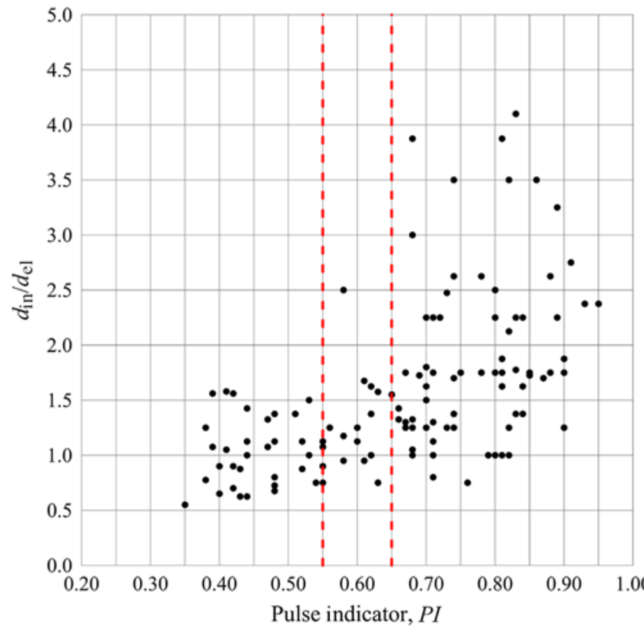

Figure 3. Ratio of the inelastic to the elastic displacement for single-degree-of-freedom systems with period equal to half the pulse period versus PI. Dashed lines correspond to the proposed thresholds for pulse-like and non-pulse-like records. The color version of this figure is available only in the electronic edition.

It can be seen from Figure 2 that, for the majority of the records, the new PI results in similar classification of the records with the Baker's PI. Specifically, the majority of the records which are classified as pulse-like based on the Baker's PI (denoted by solid and open circles) possess a value of the new PI larger than the threshold of $\mathrm{PI}_{cr,\max} = 0.65$, thus they are also classified as pulse-like by the new approach. Similarly, the majority of the records that are classified as non-pulse-like based on the Baker's PI (denoted by gray crosses) possess a value of the new PI smaller than the threshold of $\mathrm{PI}_{cr,\min} = 0.55$, thus they are also classified as non-pulse-like by the proposed classification. It is interesting to note that the new approach narrows the ambiguity zone considerably, compared with Baker' s classification.

The proposed classification was also checked against the inelastic response of SDOF structures. According to Iervolino and Cornell (2008), regarding inelastic response, ground motions containing a strong pulse might produce structures with a predominant period close to half the pulse period a ductility demand μ larger than the value of the corresponding reduction factor R, which would not be expected according to the equal displacement rule ($\mu = R$). To this end, the inelastic displacement of SDOF systems with a period equal to one half of the pulse period and a yield acceleration corresponding to reduction factor $R = 4$ are computed for 124 records of the previously used database, excluding the records of the Chi-Chi earthquake, because, in their majority, they contain pulses of large period, beyond the range of periods of engineering structures. The ratio of inelastic to elastic displacement $d_{\mathrm{in}}/d_{\mathrm{el}}$ versus the proposed PI is shown in Figure 3. Note that $d_{\mathrm{in}}/d_{\mathrm{el}} = \mu/R$ and that $d_{\mathrm{in}}/d_{\mathrm{el}} = 1.0$ corresponds to the equal displacement rule. It is obvious that records having values of PI larger than 0.65, which are classified as pulse-like with the proposed method, produce inelastic displacements that, on average, are larger than 1.5 times the elastic ones, and are increasing with the value of PI. Therefore, pulse-like records produce, in general, large ductility demands, and the proposed PI can be used as a measure of this demand. On the contrary, records having values of PI lower than 0.55, which are classified as non-pulse-like, present $d_{\mathrm{in}}/d_{\mathrm{el}}$ ratios lower than 1.5, with an average value around unity, thus the equal displacement rule generally holds for these records.

There are nine cases in which the proposed method clearly contradicts the results of Baker. In these cases, the new method indicates that the records are pulse-like, whereas, based on the Baker's PI, they are characterized as non-pulse-like. These records are shown in Figure 4, together with the corresponding M&P wavelet for the predominant pulse, derived by applying the Mimoglou *et al.* (2014) methodology. On each plot, three PIs are shown, namely (1) the value of the proposed PI that corresponds to the extracted M&P wavelet, according to which the record is classified as pulse-like by the new approach; (2) the value of $\mathrm{PI}_{\mathrm{Baker}}$ provided in the electronic supplement to Baker (2007), which is based on the Daubechies wavelet and classifies the record as non-pulse-like according to Baker's criterion; (3) the value of $\mathrm{PI}_{\mathrm{Baker,(M\&P)}}$ that is derived if the extracted M&P wavelet is used in the Baker's formula (equation 2) instead of the Daubechies wavelet.

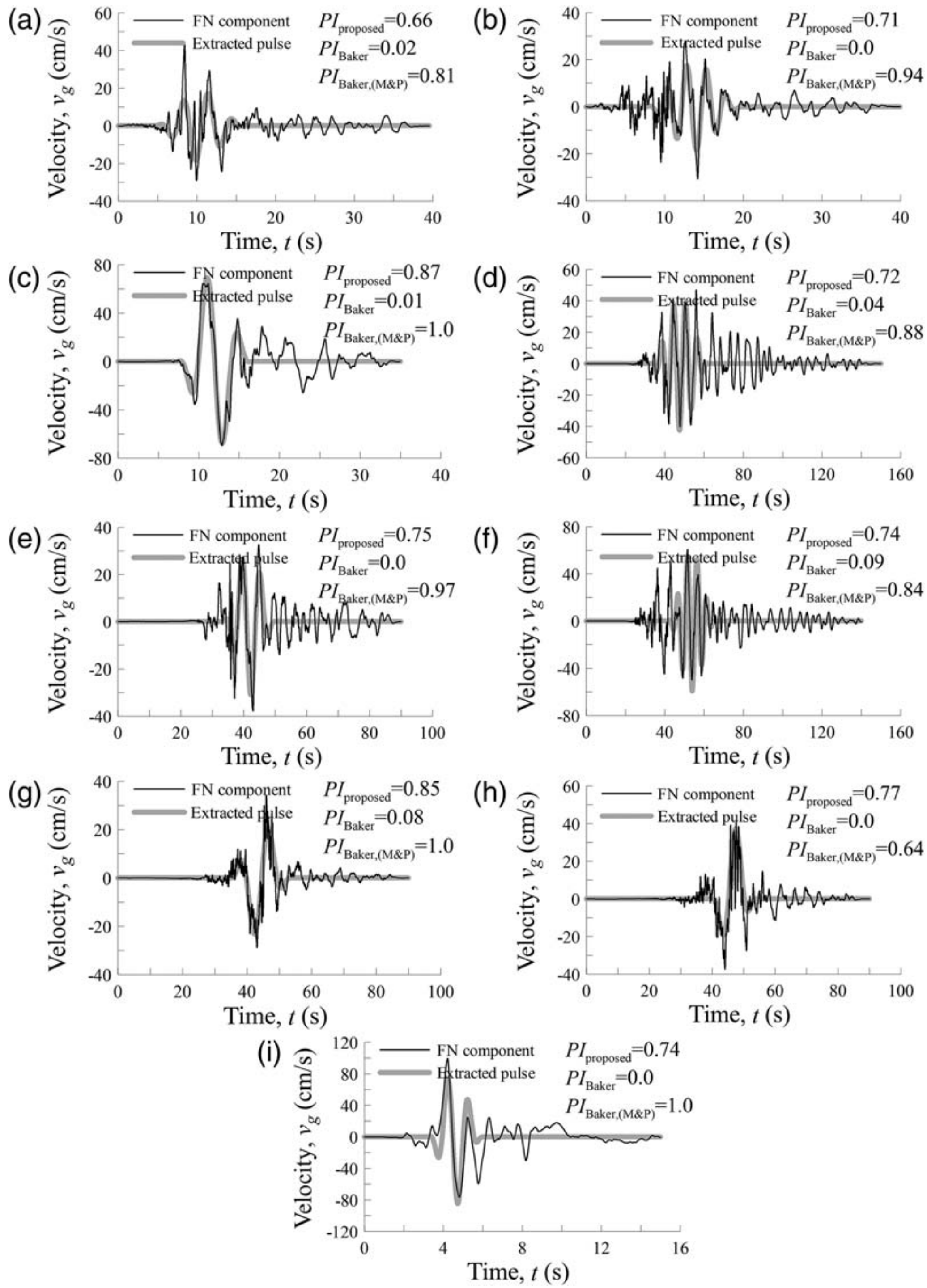

Figure 4. Time histories of the ground velocity of the normal-to-the-fault component of the nine records for which there is contradiction between the proposed approach and Baker's classification. Gray lines show the predominant pulse (Mavroeidis and Papageorgiou, 2003; hereafter, M&P wavelet). The values of the PIs shown correspond to (1) the proposed method; (2) Baker (2007); (3) Baker (2007) but using the M&P wavelet instead of the Daubechies one. Records (a) Palo Alto–SLAC Lab record of Loma Prieta, 1989, earthquake; (b) Santa Monica City Hall record of Northridge-01, 1994, earthquake; (c) Yarimca record of Kocaeli, Turkey, 1999, earthquake; (d) CHY002 record of Chi-Chi, Taiwan, 1999, earthquake; (e) CHY029 record of Chi-Chi, Taiwan, 1999, earthquake; (f) CHY104 record of Chi-Chi, Taiwan, 1999, earthquake; (g) TCU045 record of Chi-Chi, Taiwan, 1999, earthquake; (h) TCU047 record of Chi-Chi, Taiwan, 1999, earthquake; (i) Los Gatos–Lexington Dam record of the Loma Prieta, 1989, earthquake.

As can be seen from the plots of Figure 4, these records evidently contain a significant pulse; therefore, it is reasonable that they are characterized as pulse-like according to the new PI. It is, however, interesting to investigate why they are classified as non-pulse-like by Baker's PI index.

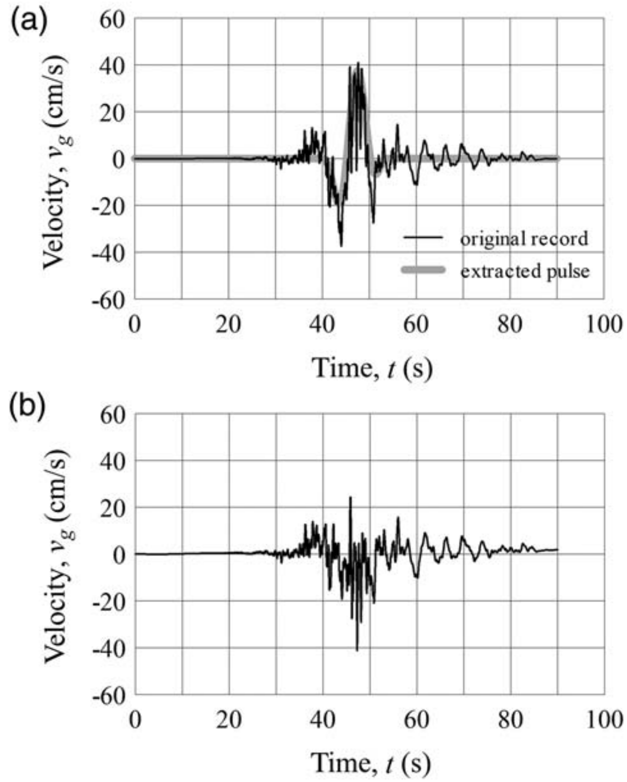

Figure 5. TCU047 record of Chi-Chi, Taiwan, 1999 earthquake: (a) original record and M&P wavelet and (b) residual record.

In most cases, the reason for this shortcoming of the Baker's method should be attributed to the inability of the Daubechies wavelet to model the predominant pulse adequately, especially if the pulse has many cycles, and not to the definition of PI itself. Specifically, the Daubechies wavelet of order four that was used in Baker (2007) seems to underestimate the energy contained in the directivity pulse, partly due to its shape and partly due to its small number of cycles. Because of the latter reason, in case of predominant pulses with many cycles, the Daubechies wavelet can capture only part of it. As a consequence, the Energy ratio increases, resulting in a small value of PI. It is noted that the M&P wavelet, which is proposed to be used in the new approach, can model pulses of many cycles more efficiently, because the corresponding parameter γ can attain large values; thus, it is considered a better approximation of the directivity pulse.

To support this argument, we calculated the PI index of the nine problematic records of Figure 4 according to Baker's formula (equation 2) but using the M&P wavelet for the representation of the predominant pulse instead of the Daubechies wavelet. The M&P wavelets were extracted applying the Mimoglou *et al.* (2014) methodology. The resulting PI values are shown in Figure 4 (denoted as $\mathrm{PI}_{\mathrm{Baker,(M\&P)}}$), and it is seen that in six cases the $\mathrm{PI}_{\mathrm{Baker,(M\&P)}}$ values are larger than the threshold of 0.85, thus they would be classified as pulse-like; in two cases (plots a and f) the $\mathrm{PI}_{\mathrm{Baker,(M\&P)}}$ values are marginally lower than the threshold of 0.85 (0.81 and 0.84, respectively), thus they would be close to be classified as pulse-like; and only in one case (plot h) the $\mathrm{PI}_{\mathrm{Baker,(M\&P)}}$ value is 0.64, clearly lower than the threshold of 0.85. Therefore, if the Baker's PI was calculated using the M&P wavelet instead of the Daubechies wavelet, most of these records would be classified as pulse-like. It is interesting to note that, in many cases, as in plots (b), (d), and (f), the M&P wavelet presents a number of cycles larger than three, indicating that the energy of the directivity pulse is distributed in many cycles.

Note that, according to equation (2), in order for the PI index to be larger than 0.85, the PGV ratio and the Energy ratio should satisfy the following inequality:

$$14.6(\text{PGV ratio}) + 20.5(\text{Energy ratio}) \leq 21.56. \qquad (7)$$

From the aforementioned cases of Figure 4, which would be classified as non-pulse-like according to Baker's PI even if the M&P wavelets were used, cases (a) and (f) present a combination of relatively high PGV ratio and Energy ratio that result in the marginal violation of equation (7).

Case (h) is different: in this case, the reason for the low PI value (equal to 0.64) is attributed to the large PGV ratio, which is equal to 0.98. The reason for this rather rare phenomenon is depicted in Figure 5, in which the time histories of the ground velocity of the original record and the residual record are shown. It is seen that, on top of the velocity pulse, there is a high-frequency signal of large amplitude (Fig. 5a). As a consequence, when the pulse is subtracted from the original record, the resulting residual record presents a large PGV, almost equal to the PGV of the original record. Therefore, the PGV ratio is close to unity; the PI value becomes small; and, thus, the record cannot be classified as pulse-like according to Baker's PI.

On the contrary, the new proposed PI is not affected by the PGV ratio, because it depends only on the correlation factor r of the velocity pulse with the original record. For the considered case of Figure 4h, this correlation factor is 0.77, significantly larger than the threshold of 0.65; thus the record is clearly classified as pulse-like.

Importance of the Assumed Wavelet for the Representation of the Predominant Pulse

As mentioned above, the new proposed PI index is set equal to the cross-correlation factor r of the significant pulse with the original record. For the set of the 221 records considered previously, the predominant pulse was calculated applying the methodology proposed by Mimoglou *et al.* (2014) using the M&P wavelet for the representation of the pulse. However, other types of wavelet can also be used for the calculation of PI. Evidently, the resulting value of PI depends on the assumed wavelet; however, this dependence does not seem to be important, at least not to a significant degree capable of changing the classification of the record, except, perhaps, in cases of records with PI values close to the thresholds.

To further investigate this issue, we calculated the new PI index for the 91 records that are characterized as pulse-like in Baker (2007) using two different types of wavelet for the significant pulse: (1) the M&P wavelet derived according to the Mimoglou *et al.* (2014) procedure as proposed in this article, and (2) the Daubechies wavelet of order 4, as given in the electronic supplement to Baker (2007). The resulting PI values are shown in Ⓔ Table S2. The results show that, for all records, the values of PI are similar for the two different wavelets considered and that, in all but seven cases, both values are larger than the threshold of 0.65. Thus, most records would be classified as pulse-like by the new approach, independently of the type of wavelet used for the representation of the predominant pulse. The seven records for which the PI index is smaller than 0.65 for one or both wavelets (shown in bold in Ⓔ Table S2) would be classified as ambiguous by the proposed method, because the PI values are larger than 0.55.

Concerning the comparison of the derived PI values, it seems that there is not any clear trend on which wavelet produces a larger PI, thus it has a better correlation with the original record. In most cases, the value of PI derived using the M&P wavelet is larger than the one derived using the Daubechies wavelet; however, there are several cases showing the opposite trend. It is noted that, because in most cases the M&P wavelet shows better correlation with the original record, it can be said that, generally, the M&P wavelet seems to be a better approximation of the directivity pulse than the Daubechies wavelet.

Conclusions

A new method is proposed for the classification of ground motions as pulse-like or non-pulse-like. The proposed PI is set equal to the cross-correlation factor r of the predominant pulse with the original record. Records with values of PI larger than 0.65 are characterized as pulse-like; records with values of PI lower than 0.55 are characterized as non-pulse-like; and records with values of PI in between are characterized as ambiguous.

The method proposed by Mimoglou *et al.* (2014), which uses the Mavroeides and Papageorgiou wavelet, is suggested for the determination of the predominant pulse. However, other appropriate wavelet types can also be used, because the proposed PI is not affected significantly by the type of wavelet used for the pulse representation.

The new PI was calculated for the fault-normal component of 221 ground motions with PGV larger than 30 cm/s from the PEER–NGA database, and 132 records were classified as pulse-like. The results were compared with those of the classification of Baker (2007) showing, in the majority of the records, good agreement. In case of differences, the new approach seems to lead to more rational results.

The proposed PI is related to the inelastic response of structures. Analyses performed for SDOF oscillators with period equal to one half of the pulse period show that records characterized as pulse-like produce, in general, inelastic displacements larger than the elastic ones, with the difference increasing with the value of PI. On the contrary, the equal displacement rule generally holds for records characterized as non-pulse-like.

Data and Resources

The electronic supplement of Baker (2007) is available at http://web.stanford.edu/~bakerjw/pulse-classification_old.html (last accessed August 2016). Pacific Earthquake Engineering Research Center Strong Motion Database is available at ngawest2.berkeley.edu (last accessed July 2013).

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