A SIMPLE ALGORITHM FOR IDENTIFYING PULSE-LIKE GROUND MOTIONS BASED ON SIGNIFICANT HALF-CYCLES

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ABSTRACT

Ground motions with strong velocity pulses are of special concern for structural engineers because they can impose extreme seismic demands on structures. Many quantitative methods have been presented in the past to identify such ground motions. However, there are still many pulse-like ground motions with multiple or irregular pulses that cannot be identified. Moreover, different methods result in contradiction classification for some ground motions. This study propose a more effective approach to identify pulse-like ground motions. To effectively characterize the obvious pulse-like features, the concept of significant velocity half-cycle is presented. The pulse energy is determined to be an indicator for quantitative identification. The result shows that the pulse energy increase, statistically, with the increase of the number of significant half-cycles in the velocity time series. Therefore, the value of the energy threshold for pulse identification is not restricted as a fixed value. Ground motions are thus classified according to the number of significant half-cycles. Then the threshold values of pulse energy for each type of ground motions are calibrated by using a training data set of manually classified ground motions. The classification results indicate that the proposed methodology can more accurately and efficiently distinguish pulse-like and nonpulse-like ground motions.

Keywords: Pulse-like Ground Motions; Significant half-cycles; Pulse energy

1. INTRODUCTION

It is well accepted that strong pulses are typically observed in velocity time series due to a variety of effects, such as forward-directivity effects (Somerville et al. 1997), surface wave effects, basin effects, etc. This type of ground motions, which is often referred to as “pulse-like ground motions”, can usually induce extreme seismic demands on structures than ordinary nonpulse-like ground motions (Luco and Cornell 2007; Champion and Liel 2012).

To capture the pulse-like features and study the influence of pulse-like input on seismic responses of structures, many methodologies have been proposed to extract and identify the dominant velocity pulse (Baker 2007; Zhai et al. 2013; Chang et al. 2016; Zhao et al. 2016). For the above identification methods, the extracted pulse by wavelets functions or mathematical models, which are simple with regular waveforms, is often used to identify whether a given ground motion is pulse-like or not. Consequently, because of the complexity and randomness of earthquake ground motions, in many cases, differences between the extracted pulse and the real pulse of an impulsive signal are apparent, which results in many pulse-like ground motions cannot be adequately classified. Mukhopadhyay and Gupta (2013) (hereafter abbreviated as the E_MG method) suggested classifying pulse-like ground motions using the maximum fractional signal energy contribution by any half-cycle of the velocity time-history. Since the indicator considers only one half-cycle, it may lose effectiveness in identifying

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ground motions with multiple strong pulses.

Based on the intrinsic pulse feature, this study develops a simple, automated and more efficient identification method. In this study, the concept of the significant velocity half-cycles is firstly presented. Ground motions are then categorized into several groups according to the number of significant velocity half-cycles; and the pulse energy is used to be an indicator to develop a quantitative identification criterion for each type of ground motions.

2. IDENTIFICATION BASED ON SIGNIFICANT VELOCITY HALF-CYCLES

2.1 Significant Velocity Half-Cycles and the Pulse Energy

A seismic velocity series is considered, in this study, as a sequence of many half-waves. As an illustration, the vibration intervals of the half-cycles are displayed in Figure 1 for a real ground motion (NGA504). The energy of each half-cycle is defined as the cumulative squared velocity during its finite time interval between two consecutive zero-crossings, at which point the velocity value equals zero. It can be calculated as

$$\Delta E_k = \int_{t_{1k}}^{t_{2k}} v^2(t)dt$$

(1)

where \(v(t)\) represents the velocity time series at time \(t\); \(t_{1k}\) and \(t_{2k}\) are the starting and ending time points in the \(k\)th half-cycle interval within the ground motion, respectively. The energy of a given ground motion can then be computed by

$$E = \sum_{k=1}^{N} \Delta E_k$$

(2)

where \(N\) is the total number of half-cycles; \(\Delta E_k\) represents the energy of the \(k\)th half-cycle in the seismic velocity series. To reflect the importance of each half-cycle, the relative energy of the \(k\)th velocity half-cycle, according to equation (2), can be defined as

$$E_k = \frac{\Delta E_k}{E}$$

(3)

The larger the \(E_k\) is, the more significant the velocity half-cycle is.

For the pulse-like ground motions, it is obvious that the velocity time series are dominated by visible strong pulses. Some pulse-like ground motions have only one dominant pulse within the velocity time history (see Figure 2(a)); whereas some possess multiple velocity pulses and/or irregular pulse (see Figure 2(b)). Because of the complexity of pulse-like ground motions, it becomes a challenge for earthquake engineers to provide a very effective identification procedure. Fortunately, regardless of the number of pulses and the irregularity of the waveforms, the common feature for all types of pulse-like ground motions is the appearance of one or more significant half-waves in the velocity time history, which makes a large contribution to the total energy and is the most important characteristic for pulse-identification. Therefore, to characterize the intrinsic pulse-like feature, the concept of significant velocity half-cycles is introduced in this study. By inspection of the identification results, the threshold value for the significant half-cycle is defined as its relative energy ratio being equal to or greater than 0.1 (i.e., \(E_k > 0.1\)). As illustrated in Figure 2(a), the ground motion time series has two significant half-cycles, and the corresponding relative energy are 0.380 and 0.499, respectively. Accordingly, the number of significant half-cycles for the velocity time series in Figure 2(b) is 4, and the energy ratios are 0.273, 0.141, 0.156 and 0.300, respectively.
Figure 1. Illustration of the vibration intervals of the half-cycles for the EW component of the NGA 504; the velocity series between each dashed curve is the identified half-cycle.

Figure 2. Example of pulse-like ground motions. (a) A pulse-like ground motion with single velocity pulse. (b) A pulse-like ground motion with multiple velocity pulses.

To identify pulse-like ground motions more effectively, based on the intrinsic pulse-like features, the relative pulse energy (i.e., $E_P$) is defined as

$$E_P = \sum_{j=1}^{n} E_j$$

in which $E_j$ is the relative energy of the $j$th significant half-cycle in the velocity series; and $n$ represents the number of significant half-cycles. The relative pulse energy ($E_P$) for the ground motions in Figure 2(a) and (b) are 0.878 and 0.870, respectively. The relative pulse energy will be used in the following as the predictor to identify the impulsive ground motions.
2.2 Criterion for Identification of Pulse-Like Ground Motions

The approach used here is to first manually classify a set of records and then build a statistically calibrated predictor that is able to closely replicate the manual classifications. The suite of 357 ground motions listed in electronic supplement of Zhai et al. (2013) is utilized for statistical analyses. A PGV threshold level of above 30 cm/s was chosen as the criterion to exclude these low-amplitude records, which is consistent with other studies (Baker 2007; Zhai et al. 2013, Chang et al. 2016). All of the 357 ground motions are visually inspected here to produce a binary ground-motion classification. As a result, 240 ground motions can be manually classified as pulse-like.

The number of significant half-cycles and the relative pulse energy are calculated for each of the 357 records. Figure 3 illustrates the relationship between the number of significant half-cycles and the pulse energy, which indicates that the pulse energy increase with the increase of the number of significant half-cycles in the velocity time series in statistic sense. Therefore, the value of the energy threshold for pulse identification should not be restricted as a fixed value. The ground motions are classified into several distinctive types according to the number of significant half-cycles, i.e., Type-0, Type-1, Type-2, Type-3, Type-4 and Type-5 (at least five significant half-cycles in the velocity time history). For illustration, Figure 4 shows the sample velocity time series of ground motions in each of category.

![Figure 3. The number of significant half-cycles versus the pulse energy for the 357 with PGV values greater than or equal to 30cm/s.](image)

To provide a more efficient classification, there is a need for determination of a reasonable energy-threshold level for each type of earthquake ground motions, above which ground motions will be classified as pulse-like. Statistical analysis is conducted in order to achieve this target. Since pulse indicator $E_p$ takes values between 0 and 1, with high values providing a strong indication that the ground motion is pulse-like, all of the records in each category are ranked in descending order according to their values of relative pulse energy. Scatter plots of the relative pulse energy $E_p$ for the manually classified records in each type of ground motions is shown in Figure 5. It can be seen that for ground motions of Type-3, Type-4 and Type-5, the distribution of $E_p$ of pulse-like ground motions is completely separate from that of the nonpulse-like ones. For ground motions of Type-2 and Type-3, the $E_p$ values of pulse-like ground motions are also clearly separate from those of nonpulse-like ground motions, except a very small region where pulse-like overlap with nonpulse-like ground motions. It
can be concluded that the pulse energy $E_p$ has good predictive ability to distinguish pulse-like and nonpulse-like ground motions. To identify as many pulse-like ground motions as possible and ensure the false positive probability equals to 0 (or very close to 0), we determined the threshold value for each type of ground motions based on the corresponding maximum $E_p$ value of nonpulse-like ground motions. The threshold values for type-1, type-2, type-3, type-4 and type-5 ground motions are 0.30, 0.42, 0.50, 0.57 and 0.73, respectively, with which the predictor $E_p$ can reasonably reproduce the manual classifications.

Figure 4. Sample velocity time series of ground motion in each category. The identified significant half-cycles are represented by the bold line. (a) Type-0. (b) Type-1. (c) Type-2. (d) Type-3. (e) Type-4. (f) Type-5. The color version of this figure is available only in the electronic edition.

Figure 5. Scatter plots of the relative pulse energy $E_p$ for the manually classified records in each category of ground motions with markers indicating their classification.
In this study, three steps are involved in identifying pulse-like ground motions.

1: Categorizing the ground motion according to the number of significant half-cycles in the velocity time series.

2: Detecting the significant half-cycles and calculating the relative pulse energy $E_P$.

3: Classifying the pulse-like ground motion according to the energy-threshold level of the type of ground motion. If the relative energy $E_P$ is not less than the corresponding threshold value, the record will then be classified as a pulse-like ground motions.

3. COMPARISONS WITH PREVIOUS ALGORITHMS

To verify the accuracy and efficiency of the proposed identification method, comprehensive comparison analyses with several previous methods are performed in this section. Here, we concentrate on comparing four previous quantitative classification approaches with the proposed approach in this study, the Baker’s algorithm (2007), the energy method (Chang et al. 2016), the ZVP approach (Zhao et al. 2016) and the $E_{M&G}$ method (Mukhopadhyay and Gupta, 2013).

All the 357 ground motions used in this study are classified by the five different identification methods. The identification results are as follows: among the 357 ground motions, 167 records are classified as pulse-like by the method of Baker; 190 ground motions can be categorized as pulse-like based on the energy method; 177 can be classified as pulse-like ground motions via the AVP algorithm; 165 records are classified as pulse-like ground motions through $E_{M&G}$ method; and 240 are classified as pulse-like ground motions according to the method proposed in this study.

If a ground motion can be identified as pulse-like by at least one of the four previous methods, it is assigned with a number of ‘1’ to indicate the pulse feature; and if a ground motion is classified as nonpulse-like (or cannot be distinguished as pulse-like) by any of the four previous methods, it is assigned with a number of ‘0’ accordingly. Figure 6 illustrates the comparative results of the four previous methods and the proposed method. Of the 357 records with PGV values greater than or equal to 30cm/s, 226 records are classified as pulse-like by at least one of the four previous classification methods and assigned with the number of ‘1’ (in the upper section of Figure 6); and 240 records (in the lower-right section of Figure 6) are classified as pulse-like by the method proposed in this study. It can be seen from the figure that among the 226 records which are assigned with the number of ‘1’, only 6 records are not identified by the proposed method (in the upper-left section), including 3 records that can be classified as pulse-like by the Baker’s algorithm, 2 record that can be identified as pulse-like by the energy method, and 1 record that can be identified as pulse-like by the ZVP method.

Detailed information and the velocity time series of the 6 records are displayed in Figure 7. It can be seen that only the ground motions in Figure 7 (a) and (c) have significant pulse-like features. This demonstrates that 99.1% (220/222) of the pulse-like ground motions that have been identified by the four previous methods can also be successfully detected by the proposed approach.

Meanwhile, it is noted from the lower-right section of Figure 6 that there are 20 ground motions which are classified as pulse-like by the proposed method but are not detected by all the four previous methods. However, 2 out of the 20 records should be best classified as non-significant pulses or ambiguous. Thus, only 0.8% (2/240) of identified records have non-significant pulse-like features. Additionally, 8 typical velocity time series from the 18 pulse-like records are shown in Figures 8. When re-examined these velocity time series, it is found that they have more than one dominant pulses and/or irregular pulse features within the whole time series. This indicates that the proposed method is also effective in detecting pulse-like ground motions with multiple and/or irregular pulses, in addition to the pulse-like ground motions with single significant pulse.
Figure 6. Comparative identification results of the four previous methods and the proposed method. The upper-left section represents the pulse-like ground motions that cannot be detected by the proposed method; the lower-right area represents the ground motions that are classified as pulse-like but are not detected by the four previous methods.

Figure 7. Velocity time series of the six ground motions that are classified as pulse-like by one of previous methods but cannot classified as pulse-like by the method in this study. (a-c) The three records that can be classified as pulse-like by the Baker’s algorithm (2007). (d-e) The two ground motions that can be classified as pulse-like by the energy method (Chang et al. 2016). (f) The record that are classified as pulse-like by the ZVP method (Zhao et al. 2016).
Figure 8. Sample velocity time series of 8 ground motions that are classified as pulse-like only by the proposed method.

4. CONCLUSIONS

This study proposes a simple and very efficient method for quantitative identification of pulse-like ground motions. Based on the intrinsic feature of the pulse-like ground motions, the concept of significant velocity half-cycles is introduced; followed is the determination of the relative pulse energy, $E_p$, which is found to be a very effective indicator for identification. This method makes an attempt to categorize ground motions into several types according to the number of significant half-cycles, and the identification criteria are determined accordingly. The analytical study performed in this study leads to the following preliminary conclusions:

(1) The concept of significant velocity half-cycles is presented based on energy. To be specific, velocity half-cycles whose relative pulse-energy above or equal to 0.1 are considered as significant half-cycles. Ground motions are categorized into six categories (i.e., Type-0, Type-1, Type-2, Type-3, Type-4 and Type-5) according to the number of significant velocity half-cycles.

(2) The relative pulse energy is adopted to determine the identification criterion; and the threshold values for ground motions of Type-1, Type-2, Type-3, Type-4 and Type-5 are 0.3, 0.42, 0.5, 0.57 and 0.73, respectively. Ground motions with relative pulse energy values greater than or equal to the corresponding threshold values are identified as pulse-like.

(3) It is shown that only 99.1% (220/222) of the pulse-like ground motions that have been identified by the four previous methods can also be successfully detected by the proposed approach; and only 0.8% (2/240) of identified records have non-significant pulse-like features. Thus, it can accurately identify ground motions.
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6. REFERENCES


