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Pulse identification for near-fault earthquake ground motion using acceleration, velocity and displacement time histories

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Introduction

Near-fault ground motions such as those recorded in Kobe (1995) and more recently in Kumamoto (2016) have been found to have significant long period components. Visual observation of the past ground motion records led to the identification of pulse-like components in the velocity time history as one of the principal difference when compared to ordinary ground motions. A number of researches in the past have proposed various numerical models to characterize the pulse-like nature of the velocity time history of near-fault earthquakes.

While this approach of identifying velocity pulses yields a good approximation of long period components in the velocity response spectrum, the identified pulses often fail to adequately represent the corresponding acceleration and displacement time histories or response spectrums. In this study, a more comprehensive pulse identification is attempted by utilizing both, the acceleration and displacement time histories. Fundamentally, this approach is based on the response spectrum based pulse identification proposed by Trivedi and Shiohara (2016) for analyzing velocity records. Pulse identification scheme is detailed and results from the analysis of a set of near-fault ground motion records are discussed.

Pulse identification scheme

Pulse component of the ground motion is proposed to be represented by simple sinusoidal functions. Single full cycle sinusoid is adopted as velocity pulse from Trivedi and Shiohara (2016) and the corresponding acceleration and displacement pulses are derived by integrating and differentiating respectively the velocity definition as follows:

$$\ddot{u}_P(t) = \frac{2\pi V_P}{T_P} \cos\left(\frac{2\pi}{T_P}(t-t_s)\right) \quad t \in [t_s, t_s+T_P] \tag{1a}$$

$$\dot{u}_P(t) = V_P \sin\left(\frac{2\pi}{T_P}(t-t_s)\right) \quad t \in [t_s, t_s+T_P] \tag{1b}$$

$$u_P(t) = \frac{V_P T_P}{2\pi}\left(1-\cos\left(\frac{2\pi}{T_P}(t-t_s)\right)\right) \quad t \in [t_s, t_s+T_P] \tag{1c}$$

where V_P is the peak velocity of the pulse, T_P is the pulse period and t_s is the starting position of the pulse on the given ground motion time history. Note that the pulse in either domain can be adequately defined determining only three parameters: V_P, T_P and t_s. Similar to the approach used by Trivedi and Shiohara (2016), pulse defining parameters are determined by optimizing (i) the correspondence of pulse to ground motion response spectrum, (ii) the fit of pulse to the ground motion time history, and (iii) the fraction of ground motion energy represented by the pulse.

The optimization procedure for velocity pulses is reported in detail by Trivedi and Shiohara (2016) and hence not described here. Procedures for determining the representative acceleration and velocity pulses are also very similar with respective optimization equations the only difference.

Correspondence to the ground motion response spectrum is ensured by selecting the pulse amplitude ($2\pi V_P/T_P$ for acceleration pulse and $V_P T_P/2\pi$ for displacement pulse as per Equation 1) such that the pulse response spectrum peak matches the corresponding ground motion response coordinate at each selected frequency. Fit to the ground motion time history is ensured by minimizing the sum of residuals for all possible t_s. Finally, the T_P which results in the pulse with largest contribution to the ground motion energy is selected as the representative pulse. Corresponding optimization parameter, energy residual (E_R,) is given respectively for acceleration and displacement pulses as:

$$E_R(T_P) = \frac{\int_0^{t_f} \ddot{u}_R^2(t)\,\mathrm{d}t}{\int_0^{t_f} \ddot{u}_P^2(t)\,\mathrm{d}t} \tag{2a}$$

$$E_R(T_P) = \frac{\int_0^{t_f} {u_R}^2(t)\,\mathrm{d}t}{\int_0^{t_f} {u_P}^2(t)\,\mathrm{d}t} \tag{2b}$$

where $\ddot{u}_R$ and u_R are the residual acceleration and displacement time histories defined as:

$$\ddot{u}_R(t) = \ddot{u}(t) - \ddot{u}_P(t) \tag{3a}$$

$$u_R(t) = u(t) - u_P(t) \tag{3b}$$

and t_f is the length of the ground motion record.

Analysis Results

Application of the proposed pulse identification scheme is illustrated for an earthquake record from 1989 Loma Prieta earthquake recorded at Gilroy Array #2. Representative pulses obtained through pulse identification in acceleration, velocity and displacement time histories are expressed in Figure 1. Time histories and response spectrum of the identified pulses are shown in comparison to the recorded ground motion. Immediately apparent from the respective time histories is the different pulse period (T_P, width of the pulse on time axis) of the identified pulses. T_P of the pulses identified in acceleration time history (A-Pulse,) velocity time history (V-Pulse) and displacement time history (D-Pulse) are observed in increasing order (0.6 s, 0.9 s and 3.1 s respectively.) Moreover the pulses are identified over different positions on the time axis, indicating the different waveforms of the original ground motion picked through either of the pulse identification procedures. Consequently, the corresponding response spectrum plots also show only a small range of frequency ranges being represented well by different pulses. It is not possible to pick a single pulse that offers the closest match to ground motion response spectrum over all frequency ranges but a combination of two or all of the identified pulses might offer the closest approximation.

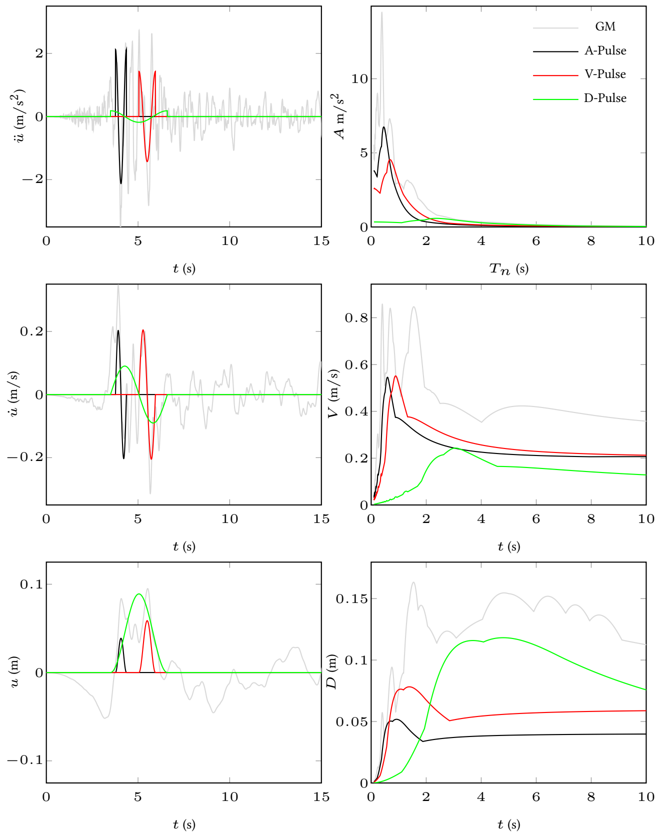

Figure 1: Time history and response spectrum of the identified representative pulses for Loma Prieta 1989 earthquake

Characteristics of the pulse identification scheme are further explored by analyzing a set of 101 near-fault ground motion records obtained from the NGA ground motion database (Ancheta et al., 2014). T_P for the representative pulse obtained through the A-Pulse and D-Pulse identification schemes are compared against the T_P for V-Pulse in Figure 2. The database exhibits ground motion records with V-Pulse T_P spread over a broad range (0 s to 10 s.) A-Pulse identification scheme largely results in short period being identified as the A-Pulse T_P takes values in the range of 0 s to 2 s only, irrespective of the corresponding V-Pulse T_P. D-Pulse identification scheme, on the other hand, shows a more complicated behavior. For ground motions with V-Pulse T_P in the range of 0 s to 4 s, D-Pulse identifies a larger period pulse than V-Pulse. And for the ground motions with V-Pulse T_P in the longer period range of 4 s to 10 s, D-Pulse identifies pulses with a comparatively shorter T_P.

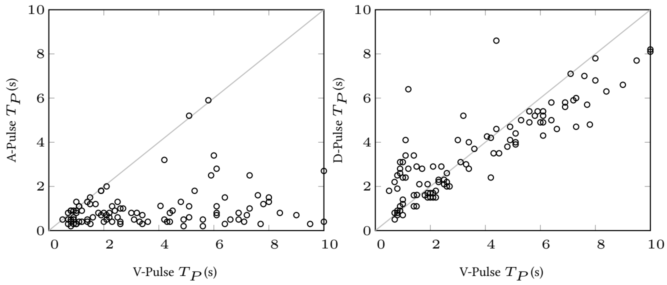

Figure 2: Comparison of pulse period of the identified representative pulses for 101 near-fault ground motions of the NGA database

In light of this discussion, it may be prudent to conclude that pulse-like ground motion characterization may not be satisfied with a single long period velocity pulse. Recognition of other pulses, such as those identified from the acceleration or displacement time histories can significantly improve the correspondence between the recorded motion and the identified pulse. This observation regarding the presence of multiple pulses was also identified by Lu and Panagiotou (2014) who used a modified wavelet method to identify secondary and tertiary dominant frequencies in the near-fault ground motion record.

Conclusion

In this study, a pulse identification scheme for identifying conventional velocity pulses in near-fault earthquake ground motions is expanded with modified pulse definitions for identifying pulses by analyzing the acceleration and displacement time histories as well. Application of the proposed scheme to a large database of near-fault records shows the varying nature of pulses identified by the either approaches. Such observations support the case for using multiple pulses for adequately characterizing near-fault earthquake ground motions.

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