Response-spectrum based pulse identification for near-fault earthquake ground motions

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Introduction

Ground motions recorded close to the earthquake source, particularly in the direction of rupture propagation, are found to have a characteristic long-period pulse-like component. This pulse component comprises a significant portion of the energy released during the earthquake and is crucial in the response evaluation of structures in the near-fault zones.

A wide array of approaches have been studied in the past to identify this coherent pulse component, especially in the velocity time history of record (Mavroeidis and Papageorgiou, 2003). Mathematical functions or wavelets defined by a multitude of parameters have been used in the past to represent the pulse component of ground motion. Even though these schemes result in a good representation of the pulse motions, the proposed parameters have little physical interpretation in terms of the earthquake magnitude and hence have limited utility in building design. Also, since these pulse identification schemes are based solely on the time-history of the recorded motion, pulses identified by such methods often fail to match the response spectrum of the actual ground motion (Lu and Panagiotou, 2014).

This study explores a different method for identifying the dominant pulse component in near-fault ground motions based on the response spectrum of the recorded motions and the method of least squares. The pulse component is represented by a simple sinusoidal pulse defined by two parameters, namely pulse period and amplitude, both of which have been identified in the past to be related to the earthquake magnitude though ground motion attenuation relationships (Somerville et al., 1997).

Pulse Identification Scheme

Main premise of the proposed pulse identification scheme is that the dominant pulse identified from the given velocity-time history represents a large fraction of the total ground motion energy. The proposed pulse identification procedure may be enumerated as, (i) defining a simple pulse to represent the dominant component of the recorded ground motion, (ii) identifying the most appropriate position for the generated pulse on the velocity-time history of the record based on the method of least squares, and (iii) estimating the fraction of ground motion energy represented by the identified pulse. This scheme is followed successively for a range of frequencies. The dominant ground motion pulse for the corresponding record is then identified with the pulse frequency that represents the largest portion of ground motion energy.

Representative Pulse

Dominant pulse component of the given velocity-time history is proposed to be represented by a single cycle sinusoid as expressed mathematically by the equation (1).

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

Where V_P is the peak velocity of the pulse, T_P is the pulse period, and t_s is the starting point of the pulse. In the proposed pulse identification scheme, a set of representative pulses are evaluated corresponding to a range of frequencies. Peak velocity for each frequency can be estimated through the velocity response spectrum coordinate of the record at that frequency. Determination of the pulse velocity through the response spectrum can be explained through figure 1.

Velocity response of the representative pulses with the same pulse period ($T_P = 3\,\mathrm{s}$) but varying pulse velocity ($V_P = 1$ to $3\,\mathrm{m/s}$) and damping at 5% as shown in the figure demonstrates that the peak velocity response for a given pulse frequency is a linear function of the pulse velocity. This relation is exploited in the proposed scheme to generate representative pulses for a range of frequencies and peak velocities corresponding to the velocity response spectrum of the recorded ground motion.

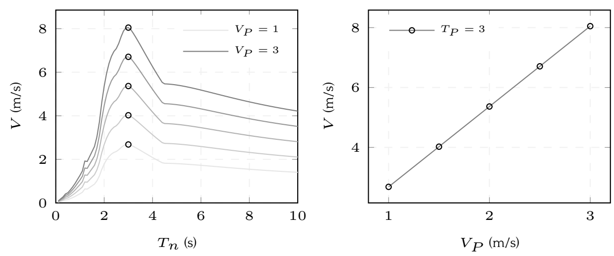

Figure 1: Peak pulse velocity determination

Method of Least Squares

Representative pulses identified with a given T_P and V_P need further identification of the pulse start time (t_s) to complete the pulse definition as per equation (1). Method of least-squares is therefore used to find the best fit position for the given pulse on the time-history of the record. If the velocity-time history of the recorded motion is represented by $\dot{u}(t)$ and corresponding pulse component is represented as $\dot{u}_P(t)$, the residual ground motion component can be expressed as,

$$\dot{u}_R(t) = \dot{u}(t) - \dot{u}_P(t) \tag{2}$$

For a representative pulse with any t_s, the corresponding sum of squared residuals for minimization with the method of least squares can be is expressed as,

$$\alpha = \int_0^{t_f} \dot{u}_R^2(t)\,\mathrm{d}t \tag{3}$$

Where $t = 0$ to t_f represents the length of the ground motion. Best fit pulse is determined with t_s for which α takes the minimum value among all possible values of t_s from 0 to $t_f - T_P$.

Residual Energy Ratio

Portion of ground motion energy represented by the pulse component can be indicated by the ratio of the residual motion energy to the pulse component energy as indicated by the following expression,

$$E_R = \frac{\int_0^{t_f} \dot{u}_R^2(t)\,\mathrm{d}t}{\int_0^{t_f} \dot{u}_P^2(t)\,\mathrm{d}t} \tag{4}$$

For a pulse-like ground motion, the pulse component comprises a large portion of the total energy hence the ratio of the residual to pulse component energy is low. Among the range of frequencies for which the representative pulses are evaluated, the one that results in the lowest residual energy ratio (E_R) is identified as the dominant pulse for the given ground motion.

Analysis Results

Pulse identification scheme described in the previous section is illustrated here with an example application. The 1979 Imperial Valley-06 earthquake recorded at the El Centro Array #6 station located at distance of 1.35 km from the rupture is chosen for this purpose. This ground motion has been obtained from the NGA ground motion database (Ancheta et al., 2014) and is classified as a pulse-like ground motion in the database. Figure 2 illustrates the identification scheme and the identified dominant pulse for this ground motion.

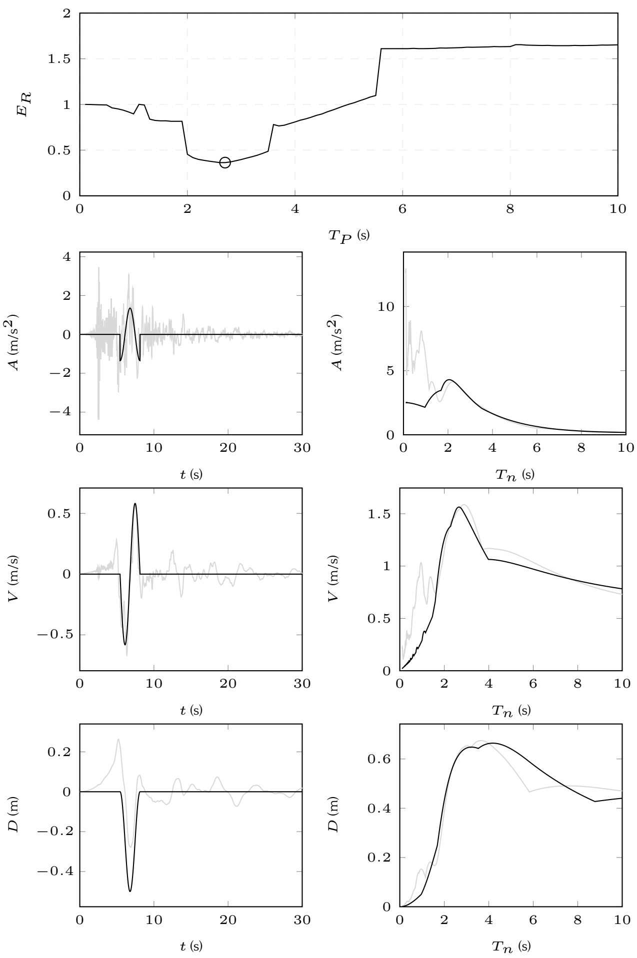

Figure 2: Demonstration of the proposed pulse identification scheme

First plot shows the residual energy ratio (E_R) as calculated for representative pulses with pulse period ranging from 0 to 10 s. As indicated on the plot, the residual energy ratio (E_R) reaches a minimum value of about 0.36 corresponding to a pulse period of 2.7 s indicating that a large fraction ($1 - 0.36 = 0.74$) of the ground motion energy is represented by the representative pulse at this frequency. On the other hand, E_R exceeds unity for pulse periods above 5 seconds meaning that the representative pulses at these frequencies have low correspondence with the recorded time history.

The representative pulse thus identified with ground motion energy and the residual energy ratio also offers significant representation with the time-history and response spectrum of the recorded ground motion. Identified pulse offers close resemblance to not just the velocity-time history but also matches well with the trend in acceleration and displacement time histories around the pulse. The identified pulse, being a low frequency phenomenon, does not match well with the high frequency components of the acceleration time-history but it suitably represents the approximate trend in the given time frame. Finally, 5% damped response spectrum plots for the identified pulse and the recorded ground motion are also shown. Close match is observed especially around the pulse period of the identified pulse and subsequent lower frequencies. Identified pulse also offers good representation of the of the acceleration response spectrum at long period range which is characteristically high for near-fault ground motions.

Conclusion

In this study a new approach for the identification of pulse component in near-fault ground motions based on the velocity response spectrum has been investigated. A simple sinusoidal pulse model is utilized to generate the representative pulses and the pulse that represents largest portion of ground motion energy is chosen as the dominant pulse of the ground motion. Demonstration of the proposed scheme on a near-fault earthquake record identifies a pulse that is in good agreement with the time-history of the record and also matches well with the response spectrum in long period range.

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