Identification of pulse-like ground motions during the 1994 Northridge Earthquake

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Abstract. The 1994 Northridge Earthquake is selected as an example to discuss the ability of three pulse-like ground motion identification methods. Wavelet analysis, peak-point method (PPM) and zero velocity point method (ZVPM) are used. Pulse indicator (PI) is calculated to identify pulse-like ground motions from 314 near-fault records. Peak ground velocity (PGV) and pulse period (Tp) of the pulse-like motion from these three methods are compared. Most of the pulse periods from PPM are smaller than those from the other two methods. And, most stations with pulse-like ground motions are located on the hanging wall. The effect of velocity pulse on response spectra is investigated further. The amplification at the hanging wall stations is more serious than that at the footwall stations.

1. Introduction

Permanent displacement and intensive velocity pulses are the characteristics of near-fault ground motions. The latter is the result from rupture directivity effect in some cases, which causes serious damage to long-period engineering structures, such as long-span bridges, lifeline systems, high-rise or base-isolated buildings. When the fault rupture propagates to the site of the observation station and the rupture velocity is close to the shear wave velocity of the medium, the rupture directivity effect will appear. In the forward direction of the rupture, the amplitude is higher and the duration is shorter than those in the opposite direction. The spatial distribution and time-domain characteristics of ground motions are strongly affected by the rupture process by the reason of the seismogenic fault and directivity effect can be arised by many factors, such as the uneven of the fault, the focal mechanism, the variety of the rupture velocity in different medium, the diversity of the asperity, the attenuation of the ground motion and the depth of the fault (Wang, 2004[1]). Somerville (1993[2]) explained the causes of pulses from the perspective of energy accumulation, and then he analyzed near-fault records and found the reason that long-period pulse appeared in fault-normal (FN) components (Somerville, 1997[3]). Xu and Hu (2008[4]) compared the forward directivity effect and fling-step effect on the FN and fault-parallel (FP) components in the case of strike-slip earthquake. It was found that the peak ground motion velocity (PGV) and the peak ground displacement (PGD) in the FN direction were larger than those in other directions. Although the directivity effect was observed several decades ago, induced structural damage, its mechanism and identification methods were studied late and progressed slowly. Baker (2007[5]) proposed a quantitative identification method based on wavelet analysis and developed in 2014, then various methods, such as PPM (Peak Point Method), Hilbert-Huang Transform Method (Zhang, 2003[6]), cumulative absolute displacement (CAD) method (Vassilik i et al, 2014[7]) and S-transform method (Ghaffarzadeh, 2016[8]), were developed in recent years. These
identification methods contributed to understand the mechanism of pulse-like ground motion. Three methods of them, wavelet analysis, PPM and ZVPM, are borrowed to identify pulse-like ground motion from the records of the 1994 Northridge Earthquake, and the identified pulse parameters, PGV and pulse period \((T_p)\), are compared in this paper. Further, we investigate the effect of pulse amplification on the response spectra and the difference between the amplification at hanging wall stations and that at footwall stations.

2. Velocity pulse identification from observed near-fault ground motions

2.1. Near-fault ground motions

The \(M_w6.7\) Northridge Earthquake, occurred in the San Ferrando Canyon on January 17, 1994, caused serious damage of engineering structures. This is a reverse-fault earthquake with the size of 18 km×24 km, 122° strike and 40° dip angle. The fault plane ruptured from a depth of about 17.5km to about 5km beneath the surface, along which the rupture propagated upward and northwestward at rate of about 3km/s in 8s following the initial break. 314 acceleration records at the 157 stations are collected from the Pacific Earthquake Engineering Research Center, and the distribution of these stations and epicentre are shown in Figure 1(a). 34 records on EW direction with rupture distance less than 60km at hanging wall stations and footwall stations are shown in Figure 1(b).

![Figure 1(a). Stations and the epicenter.](image1)

![Figure 1(b). Accelerogram.](image2)

2.2. Wavelet analysis methods

We borrow three methods to identify the pulse-like ground motions from these 314 records, which are preprocessed to rotate from EW and NS components to FP and FN components. First method is based on wavelet transform (Baker, 2007; 2014\(^\text{[5]}\)\(^\text{[9]}\)). The 4th Daubechies wavelet is used as mother wavelet for the continuous wavelet transform, and then the wavelet coefficient with the largest absolute value is picked up. The wavelet associated with this coefficient determines the period and position of the pulse. The selected pulse has the largest energy due to the equivalence between the wavelet coefficient and the energy of the relevant wavelet. The initial seismic record continuously performs wavelet transformation to extract the maximum velocity pulse time history. After 398 records containing pulses of NGA-West2 was classified and calculated, Baker (2007\(^\text{[5]}\)) finally gave the expression of pulse indicator \((PI)\) as in equation (1).

\[
PI = \frac{1}{1 + e^{23.3+14.6(PGV\text{ratio})+20.5(energy\text{ratio})}}
\]  \(\text{(1)}\)
In further research, Shahi and Baker (2014 [9]) found that velocity pulses not only exist in the direction of FN and FP, but may also appear in the direction perpendicular to the fault strike. In a certain area near the direction, they proposed the concept of the strongest velocity pulse direction and a multi-component ground motion velocity pulse recognition method based on continuous wavelet transform, after extracted the strongest velocity pulse direction component from the velocity record. New indicator $PI$ is calculated by equation (2) and equation (3).

$$PC = 0.63 \times PGVratio + 0.777 \times energyratio$$

$$PI = 9.384(0.76 - PC -0.0616PGV)(PC + 6.914 \times 10^{-4} PGV -1.072) - 3.179$$

The main idea is to linearly combine two orthogonal horizontal components (usually FN and FP components), perform continuous wavelet transformation, and select the $\beta$ component corresponding to the maximum wavelet coefficient, and then it is judged according to $PI$. If the $\beta$ component satisfies the $PI > 0$, represented this orientation contains velocity pulse. An example is shown in Figure 2.

![Figure 2. Northridge station Jensen Filter Plant Administrative Building identified the pulse by wavelet analysis.](image)

### 2.3. Energy methods

The second method PPM is proposed by Zhai and Chang (2013 [10]), which is an energy-based pulse identification and extraction method. The pulse model is proposed by Dickinson and Gavin (2011 [11]), in which peak amplitude $V_p$, period $T_p$ and number of fitted pulse $N_c$, phase parameter $\phi$ and pulse peak moment $T_{pk}$ are the model parameters, and the function is expressed by equation (4).

$$v_p(t,V_p,T_p,N_c,T_{pk},\phi) = V_p \exp \left[ -\frac{\pi^2}{4} \left( \frac{t-T_{pk}}{N_c T_p} \right)^2 \right] \cos \left( 2\pi \frac{t-T_{pk}}{T_p} - \phi \right)$$

In order to simplify the calculation model, $N_c = 1$ and $\phi = 0$ are given. The corresponding parameters $T_p$, $V_p$, $T_{pk}$ are determined by searching the best match of the original seismic signal and $V_p$ calculated by equation (4). Based on this energy method, Zhao (2016 [12]) proposed ZVPM to identify multi-pulse ground motions, which is the third method we use here. The threshold of pulse index $PI$ established by Baker (2007 [5]) is 0.15 and 0.85, the ground motions with the index value larger than 0.85 and smaller than 0.15 are classified as pulse and nonpulse, respectively. The threshold of energy index $E_p$ established by Zhai (2013 [10]) is 0.3. PPM aims to identify the single pulse ground motions and lack of effectiveness to identify the multi-pulse ground motions. ZVPM is on the basis of the trigonometric function and can detect the potential velocity pulses. The velocity pulse caused by the directive effect generally contains a main pulse and a secondary pulse, which the pulse period between them is generally close. The pulse period determined by ZVPM is the time difference between the start and end of the pulse and the zero line to identify multi-pulse ground motion. Therefore, different standards should be defined for different pulse-like records, if there is a single velocity pulse, the energy ratio threshold of the dominant velocity pulse with a period of 0.5s is defined as 0.3. By analyzing a large number of ground motions with multiple velocity pulses, the different vibration interval is determined the energy ratio of 0.6, 0.8 and 0.9 as the discriminating index of double-pulse,
three-pulse and four-pulse ground motion. Figure 3 shows example of different methods to extract velocity pulse.

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Figure 3. Northridge station Jensen Filter Plant Administrative Building identified the pulses by PPM and ZVPM.

2.4 Results

We did not combine the 314 FN and FP components from the Northridge Earthquake, in which 17 FN components are identified as pulse-like ground motions by these three methods, and the pulse parameters are listed in Table 1. The pulse amplitudes extracted by PPM and ZVPM are similar; the pulse periods are slightly different, most identified by PPM are smaller than the results from the other methods.

Table 1. Identified pulse parameters

| Station number | Baker07 | Baker14 | PPM | ZVPM | Baker07 | Baker14 | PPM | ZVPM |
|----------------|---------|---------|-----|------|---------|---------|-----|------|
| RSN953         | -       | -       | 1.2 | 1.2  | -       | -       | 73  | 57   |
| RSN960         | -       | 2.1     | 1.3 | -    | -       | 46      | -   | 58   |
| RSN963         | -       | -       | 1.7 | 1.6  | -       | -       | 51  | 63   |
| RSN982         | 3.1     | 3.1     | 2.9 | 3.3  | 151     | 168     | 154 | 158  |
| RSN983         | 3.5     | 3.5     | 0.8 | 3.3  | 66      | 76      | 88  | 64   |
| RSN1003        | 1.0     | 1.0     | -   | -    | 43      | 43      | -   | -    |
| RSN1004        | 0.9     | 0.9     | 0.6 | 1.0  | 77      | 102     | 43  | 41   |
| RSN1013        | 1.6     | 1.7     | 1.2 | 1.7  | 86      | 79      | 82  | 79   |
| RSN1044        | 1.4     | 1.0     | 0.8 | -    | 116     | 121     | 112 | -    |
| RSN1045        | 2.9     | 2.9     | 2.1 | 2.4  | 118     | 116     | 102 | 112  |
| RSN1050        | 0.6     | -       | 0.5 | -    | 50      | -       | 48  | -    |
| RSN1052        | 0.7     | -       | -   | 56   | -       | -       | -   | -    |
| RSN1054        | 1.2     | 1.2     | 1.2 | 1.2  | 76      | 83      | 68  | 71   |
| RSN1063        | 1.2     | 1.2     | 1.0 | 1.0  | 119     | 115     | 117 | 114  |
| RSN1084        | 2.9     | 3.0     | 2.5 | -    | 103     | 119     | 86  | 150  |
| RSN1085        | 3.5     | 3.5     | 0.8 | 3.4  | 113     | 110     | 99  | 119  |
| RSN1086        | 2.4     | 2.3     | 2.4 | 2.8  | 67      | 71      | 87  | 63   |

3. The effect of hanging wall on velocity pulse

The hanging wall effect is an important feature of near-fault ground motions and significantly appeared in thrust-fault earthquakes. (Someviller, 2000[13]). Hanging wall effect means the observed peak ground acceleration and short-period response spectral acceleration at hanging wall stations are greater than those at footwall stations, as shown in Figure 1(b). Hanging wall effect in the Northridge Earthquake was observed by Someviller (1996[14]), and the existence of hanging wall effect within the fault distance of 5-20km was certificated. In the case of equal fault distance, the station on the hanging wall is closer to the rupture plane than that on the footwall, where more energy received and resulted in different characteristics. In the Northridge earthquake, RSN982, RSN983, RSN1004,
RSN1013, RSN1063, RSN1084, RSN1085 and RSN1086 are hanging wall stations; RSN960, RSN1044, RSN1050, RSN1052 are footwall stations; RSN1054, RSN1045 and RSN963 locate in neutral zone (Wang, 2010[15]). The stations with pulses-like ground motions identified by different methods above are shown in the Figure 4, in which the red triangle denotes the stations with identified velocity pulse.

![Figure 4. (a) PPM (b) ZVPM (c) Baker07 method (d) Baker14 method](image)

It can be found in Figure 4 that most of the stations with pulse-like ground motions are located on the hanging wall. In order to further explore the influence of the hanging wall effect and directivity effect, Figure 5 shows the effect of the velocity pulse on the response spectra of records at the hanging wall and footwall stations with fault-distance less than 40km.

![Figure 5 (a). Response spectrum of records at hanging wall station.](image)
Figure 5 (b). Response spectra of records at footwall station.

The gray shadow indicates the amplification caused by the pulse. It can be found that the pulse amplification effect on the records at the hanging wall stations is more serious than that at the footwall stations. Thus, both ground motion amplitudes and pulse amplification at the hanging wall stations are larger than those at footwall stations. In Figure 5(a), the amplification of RSN1004, RSN1013 and RSN1063 records concentrated at short periods, which might be caused by hanging wall effect; the amplification of RSN982, RSN983, RSN1084 and RSN1085 at short periods tapers to zero around 1s, then increases and extends to long periods, which might imply the conversion of hanging wall effect to directivity effect. The four footwall stations are all located in front of the rupture, RSN960 is located directly in front of the rupture, and RSN1044, RSN1050 and RSN1052 are close to the rupture surface projection. The long-period amplification of RSN960 record might be dominated by directivity effect.

4. Conclusion

The 1994 Northridge Earthquake is taken as an example, we compare the pulse identification results from 314 strong earthquake records by the methods of wavelet analysis, PPM and ZVPM. The pulse amplitude extracted by the PPM and ZVPM are similar, and the pulse period are slightly different. Most of the pulse periods extracted by PPM are smaller than those of the other methods. Most of the stations with pulse-like ground motions, identified by the three methods, are located on the hanging wall. By analyzing the amplification effect of the velocity pulse on the response spectra, it is further clarified that the influence of the hanging wall effect is not only on the peak ground motion, but also on the pulse amplification. Three stations (RSN963, RSN1045, RSN1054) located neither at the hanging wall nor at the footwall, which are on the rupture direction, so the directivity effect could be dominated. For those stations both at hanging wall stations and on rupture direction, the contributions from these two effects is observed on different period ranges.

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