QUANTITATIVE IDENTIFICATION OF PULSE-LIKE GROUND MOTION BASED ON RELATIVE ENERGY ZERO RATE

N. Li¹, P. Liu², Z. X. Li³ and L. L. Xie⁴

ABSTRACT

Near-fault seismic records have pulse-like wave motion at a high probability, and the pulse-like ones cause severe damage to structures. Qualitative identification of a pulse-like ground motion using statistical analysis method or phenomenology study on the shape of a pulse was still not completed. A few qualitative criteria considering energy characteristic of a seismic record were proposed. Further, due to the uncertainty and complexity of seismic records, the correlation and regression description of a pulse-like motion is not suitable for all the near-fault records. A quantitative identification method is proposed for the pulse-like seismic records, which uses an innovative parameter, relative energy zero rate (REZR). An effective extraction algorithm of the parameters for pulses is realized by combining the energy changing and zero crossing ratio. The proposed method is validated. Compared with the peak point method (PPM) and the wavelet method, the reasonability of the new algorithm is illustrated. Then, mathematical prototypes for the pulse-like waveform are introduced. The parameter values of the simplified waveforms are regressed using REZR. The forward directivity effect is illustrated using the simplified wave motion as an example. The influence of the forward directivity on the design response spectrum was illustrated. At last, the modified elastic design spectrum and inelastic design spectrum are given. The fling-step effect and other near-fault damage effects can be taken into account in the design using the same approach.

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ABSTRACT

Near-fault seismic records have pulse-like wave motion at a high probability, and the pulse-like ones cause severe damage to structures. Qualitative identification of a pulse-like ground motion using statistical analysis method or phenomenology study on the shape of a pulse was still not completed. A few qualitative criteria considering energy characteristic of a seismic record were proposed. Further, due to the uncertainty and complexity of seismic records, the correlation and regression description of a pulse-like motion is not suitable for all the near-fault records. A quantitative identification method is proposed for the pulse-like seismic records, which uses an innovative parameter, relative energy zero rate (REZR). An effective extraction algorithm of the parameters for pulses is realized by combining the energy changing and zero crossing ratio. The proposed method is validated. Compared with the peak point method (PPM) and the wavelet method, the reasonability of the new algorithm is illustrated. Then, mathematical prototypes for the pulse-like waveform are introduced. The parameter values of the simplified waveforms are regressed using REZR. The forward directivity effect is illustrated using the simplified wave motion as an example. The influence of the forward directivity on the design response spectrum was illustrated. At last, the modified elastic design spectrum and inelastic design spectrum are given. The fling-step effect and other near-fault damage effects can be taken into account in the design using the same approach.

Introduction

Seismic records with pulse were found in 1957 Port Hueneme earthquake firstly, then researchers and engineers began to focus on the damage potential to different structures [1]. Pulse-like wave motions have particular properties, such as the forward directivity and fling-step effects, which is well-known for researchers. However, there is few engineering code taking into account that effect with a quantitative indicator. More and more researchers realized the importance of the characteristics of near-fault ground motions on different structures. In the latest decade, many studies developed different predictive relationships and parameters that characterize pulse-like ground motions in the near-fault areas [2]. The statistical regression of velocity pulse period was provided using different seismic record datasets [3-11]. Many continuous function and formula for velocity time history are given by different researchers, such

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as rectangular [12, 13], triangle [13, 14], quadratic [14], sinusoidal [11, 13, 15-17], harmonic and piecewise pulse functions [18]. The proposed equivalent pulse-like waveform models are well represented for theoretical analysis and engineering applications. However, they do not indicate whether a given ground motion contains a velocity pulse. Baker [9] and Shahi [1] developed a quantitative classification scheme to identify pulse-like ground motion based on wavelet transform theory. However, this formula cannot represent the time series with several discontinuous pulses in a waveform. Yang et al. [19] proposed a site-based stochastic near-fault ground motion model that combines a wavelet model of the pulse with a stochastic model of the high-frequency content. Since the energy is most concentrated in the pulse [20], over 85% of the total energy input into the structure occurs in a relatively short duration, usually no more than 12 seconds, near-fault pulses affect the seismic performance of structures adversely. Zhai et al. [7] present a quantitative method for identifying velocity pulse based on the energy of the pulse. Zhao et al. [6] propose a quantitative method to distinguish the special vibration region from a signal based on zero crossing rate and relative energy.

To investigate the effects of pulse-like ground motions on structural response and to gain insight into the damage potential of near-fault ground motions, it is necessary to perform the analysis of pulse effect on response spectrum, taken seismic hazard into account, and the final results of this study are for design.

Considering the design requirement, a relative energy zero ratio (REZR) is firstly proposed and used to distinguish pulse-like ground motions. Further, a new identification technique for pulse-like ground motions is presented. The reasonability of the proposed method is verified with a set of near-fault pulse-like records. The parameters, such as the period of a pulse, the amplitude of velocity, the earthquake magnitude, the intensity measurement and the local site conditions, are studied. The correlations among different parameters are investigated. Different regression models are proposed for different parameters. At last, the parameters of near-fault ground motion are used to modify the predefined design response spectrum based on the elastic design spectrum theory and the inelastic design spectrum theory.

**Problem Definition**

**Near-fault Ground Motions and Response Spectra**

Pulse-like ground motions and its damage potential for different structures are investigated in the academia and engineering community. The first design code introduced near-fault effect is UBC-97. The amplification factor for structures in the near-fault region was introduced. The design spectrum in the long period region is treated as a flat zone with a constant value. Japan and Taiwan made modification on their own seismic design codes after 1995 Kobe earthquake and 1999 Chi-Chi earthquake. They both enhanced the fortification measures for near-fault structures. However, seismic design response spectrum deduced using far-field records is used widely in the world. Although, it is recognized that there is a great difference between near-fault and far-field ground motions. Based on the comparative study on the response spectrum of near-fault and far-field ground motions, for near-fault ones, the acceleration response spectrum has a wider acceleration sensitive range. For long period range, the value of near-fault response spectrum is higher than far-field ones. For Chinese design spectrum within the period between 0.5s and 2.5s, the spectra values of near-fault records are higher than the predefined design spectra; but, for the period longer than 3s, the values are less than design spectra [21]. Further results illustrated that the characteristic
period of near-fault response spectra is longer than design spectra [21].

**Seismic Mitigation and Fortified Measures**

Many countries are using specified setback distance and seismic hazard analysis in seismic design code as the fortified measures. As far as the authors know, the design response spectra for near-fault structures are not validated nor verified, which means that there is no quantitative criterion taken the damage potential of near-fault ground motion into structure design at all [22]. With the development of resource exploitation and engineering construction, more and more structures are built in the zone which nearby or overcrossing faults, such as the dams, the expressway bridges, the pipelines, et al. For the shortage consideration in design spectrum, it is necessary to develop a common design method for near-fault structures.

**Pulse Identification and Parameters**

In order to fulfill the requirements of design and engineering application, the recorded near-fault strong ground motions need to be identified and quantitatively analyzed firstly. The equivalent model is widely accepted due to its simplicity and convenient in engineering applications. In pules wave motions, it contains several half-cycle waves usually. Velocity pulse contains half cycle ripples commonly. Study on the damage potential of pulses using ordinary/standard wave expression instead of real record is widely accepted since the ordinary/standard formula characterized the properties of pulses well. Although the time history may be different, the response spectrum matched well for both of them. The ordinary wave motion functions are rectangular, sinusoideal, triangular and square functions. The parameters of different pulse wave motion are different and have a significant influence on the damage potential of velocity pulses.

**Proposed Pulse Identification Algorithm and Physical-Based Explanation**

**Relative Energy Zero Ratio for Pulse Identification**

It is known that the seismic ground motions are non-stationary. However, it can be assumed that, for a short-time duration, the stochastic parameter of a seismic record is time-invariant. In this study, the short-time analysis technology based on the assumption of stationary of strong ground motion in a short duration is adopted.

The seismic record is divided into a series of segments (Fig. 1) using a moving window function, \( w(n) \). The window function is a weighting function with length, \( w_{\text{len}} \). The distance between the later segment and the previous one is called shifting length, \( \text{inc} \). The overlap between two adjacent segments is overlap (\( w_{\text{len}}-\text{inc} \)).

The short-time energy (STE) is calculated using the summation of squared digital signals, filtered by a window function. It can be expressed as,

\[
E(i) = \sum_{n=0}^{L-1} x_i^2(n), \quad x_i(n) = w(n) \cdot x\left((i-1) \cdot \text{inc} + n\right), \quad 1 \leq n \leq L, \quad 1 \leq i \leq f_n
\]

where, \( E(i) \) is the STE of a signal under the specified window function, which contains the energy information of the signal within a short duration. \( L \) is the length of each short duration segment, \( x_i(n) \) is the signal of the \( i \)th segment and the \( n \)th sample, \( w(n) \) is window function, \( f_n \) is the total
number of segments. The other parameters can be found in Fig. 1.

![Image of Figure 1](image.png)

Figure 1. (a) Parameters and signal processing illustration, (b) Short time average energy curve and (c) Short time average zero-crossing rate curve for a velocity time history

Then the short-time zero crossing rate is calculated. Zero crossing rate (ZCR) is defined as the number of a waveform crossing the horizontal axis in a given time duration. The short-time zero crossing rate (STZCR) is ZCR over a pre-defined short duration. In this paper, STZCR is the number of ZCR in each window, as shown in Fig. 1 (c). STZCR is

\[
Z(i) = \sum_{n=0}^{L-1} \left[ \text{sgn}[x(n)] - \text{sgn}[x(n-1)] \right] \cdot w(n)
\]

where \(\text{sgn}[\cdot]\) is the sign function.

It is interesting that, for pulse-like waveform, the STE curve has the tendency of upwards convex shape, and on the other side the STZCR has the tendency of downward convex shape. On the contrary, the energy is smaller but STZCR is large for non-pulse-like segments (STE curve is downward convex, and the STZCR is upward convex). According to the different tendencies of these two parameter, STE and STZCR are suggested to build a new parameter, relative energy zero ratio (REZR) in this research.

In order to eliminate the difference, STE and STZCR are normalized. This paper uses \(E_i\) divided by \(E_{\text{max}}\) and define it as the relative STE,

\[
ER_i = \frac{E_i}{E_{\text{max}}}
\]

The ratio of \(Z_i\) to \(Z_{\text{max}}\) is defined as the relative zero crossing ratio,

\[
ZR_i = \frac{Z_i}{Z_{\text{max}}}
\]

According to formula (3) and (4), the relative energy zero ratio (REZR) can be calculated by

\[
REZR_i = \frac{ER_i + b}{ZR_i + b}
\]

In order to prevent \(ZR_i=0\) causing an overflow, both the numerator and denominator of the fractional expression add a constant, \(b=1\). This paper used the value of the normalized STE divided
by normalized STZCR as the pulse identification parameter, REZR.

Validation of Proposed Algorithm

For clarity, the analysis procedure using REZR on near-fault ground motion (TCU068 station record during the Chi-Chi earthquake, 1999) is illustrated in Fig. 2(I). Fig. 2(I) - (a) provides the velocity time history. The energy in the pulse region is obviously larger than the non-pulse region. Fig. 2(I) - (b) shows the STE curve. The curve in the pulse region is remarkably smaller than the pulse region. The normalized STE (solid line) and normalized STZCR (dot line) are plotted together and compared in Fig. 2(I) - (d). The convex and concave of the curve intersect at two points whose distance is more or less equal to the pulse period in the original earthquake record. Fig. 2(I) - (e) shows the changes of the ratio of relative STE and relative STZCR, which is the proposed REZR curve. There are two-reversed crossing points on the curve. The distance, period of pulse $T_p$, between the two points in Fig. 2(I) - (e), equals to the horizontal distance between the two crossing points in the Fig. 2(I) - (d). The difference of the pulse region and the non-pulse region using the curve of REZR is obviously. Fig. 2(I) - (f) presents the relative cumulative energy of the identified pulse waveform. Further, the distance between the two-reversed crossing-points corresponds to the increasing region of relative cumulative energy, $E_p$. This signal processing algorithm is suitable for any seismic records. Further, this method can give out a more reasonable result. Taking ground motion record (051WCW-EW) as another example, which is illustrated in Fig. 3, there are two bulges in the diagram.

In order to validate the proposed identification method, 111 ground motions are identified using REZR, Wavelet transformation method (Baker) proposed in [9], and peak point method (PPM) proposed in [7], individually. The energy extracted from seismic records are compared and illustrated in Figs. 3(a) and 4(a). REZR extracted the most energy of a pulse-like ground motion. The period of pulses are extracted and compared in Figs. 3(b) and 4(b). REZR method has the
same results as wavelet transformation method.

A correlative analysis is carried out on the parameters of pulse and seismic event, the correlative expression for 2 parameters, X and Y, is

\[
\rho = \frac{n \sum (\ln X \ln Y) - \sum \ln X \sum \ln Y}{\sqrt{\left(n \sum (\ln X)^2 - (\sum \ln X)^2\right)\left(n \sum (\ln Y)^2 - (\sum \ln Y)^2\right)}}
\]

where X and Y are different parameters in Tab. 1. The correlative coefficients, \(\rho\), presents the correlative level of different parameters. There is 5 level of correlative of different parameters, 0.8 < \(\rho\) < 1 almost relative, 0.6 < \(\rho\) < 0.8 strongly relative, 0.4 < \(\rho\) < 0.6 medium relative, 0.2 < \(\rho\) < 0.4 almost not relative, and 0 < \(\rho\) < 0.2 not relative. Eq (6) gives out the correlative coefficient of different parameters. It is obviously that \(w_{len}\) and \(T_p\) are strongly relative. At the same time, \(w_{len}\) has strongly relative with \(T_v\) and \(M_w\). The attenuation relationship of \(w_{len}\) and \(R\) can be deduced using least square regression, and expressed as

\[
\ln(w_{len}) = -2.23 + 0.48M_w + 0.17\ln(T_v^2 + 0.62^2)
\]
Table 1 Correlation coefficients between velocity pulse and seismological parameters

<table>
<thead>
<tr>
<th>η</th>
<th>w_len</th>
<th>T_sv</th>
<th>M_w</th>
<th>R</th>
<th>PGV</th>
<th>T_p</th>
</tr>
</thead>
<tbody>
<tr>
<td>w_len</td>
<td>1</td>
<td>0.65</td>
<td>0.66</td>
<td>0.18</td>
<td>0.09</td>
<td>0.83</td>
</tr>
<tr>
<td>T_sv</td>
<td>1</td>
<td>0.70</td>
<td>0.03</td>
<td>0.15</td>
<td>0.73</td>
<td></td>
</tr>
<tr>
<td>M_w</td>
<td>1</td>
<td>0.13</td>
<td>0.17</td>
<td>0.78</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R</td>
<td>symmetry</td>
<td>1</td>
<td>0.61</td>
<td>0.13</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PGV</td>
<td>1</td>
<td>0.02</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T_p</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

As shown in Tab. 1, PGV and fault distance R are highly correlated, however, there was almost no relationship between PGV and magnitude M_w. Using the data in Tab. 1 to determine the regression coefficient by least squares fitting method. The relation between PGV and R is,

\[
\ln(\text{PGV}) = 4.71 - 0.14\ln(R^2 + 1.6^2) \quad (8)
\]

As shown in Tab. 1, the close correlation between T_p and magnitude M_w by REZR method as shown in Tab. 1. To determine regression coefficient by least squares fitting using the data in Tab. 1. The relation between M_w and ln(T_p) is,

\[
\ln(T_p) = -5.15 + 0.92M_w \quad (M_w \geq 5.6) \quad (9)
\]

Proposed Design Spectrum for Near-Fault Seismic Hazard

The typical ground motion acceleration pulses mainly include rectangle, sinusoidal, triangular and quadratic wave forms. The four acceleration pulse of forward directivity are shown in Tab. 2. For limited space, in this paper the forward directivity are discussed. Each typical pulse can be described by two parameters, amplitude \( f_0 \), and the pulse duration, \( T_p \).

Table 2. Equivalent pulse models

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Forward Directivity</td>
<td>( f_0 )</td>
<td>( f_0 )</td>
<td>( f_0 )</td>
<td>( f_0 )</td>
</tr>
<tr>
<td>( T_1 )</td>
<td>( T_2 )</td>
<td>( T_3 )</td>
<td>( T_4 )</td>
<td>( T_5 )</td>
</tr>
</tbody>
</table>

Proposed Elastic and Inelastic Design Response Spectrum

Elastic and inelastic design spectra based on simplified pulse models is illustrated in this section. Taken the triangle pulse as an example, \( M_w = 6.5 \), the epicenter distance are 5km, 10km, 15km and 20km, respectively. \( \zeta = 0.05 \). The elastic and inelastic design spectra are deduced step by step in Tab. 3.

Table 3. Design spectrum deduced step by step

<table>
<thead>
<tr>
<th>Steps for elastic design spectrum</th>
<th>Steps for inelastic design spectrum (( \mu = 2 ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Calculate PGV and T_p following Eq. (8)-(9) (for ( M_w = 6.5 ));</td>
<td>1) Divided the acceleration part of elastic design spectrum, ( A_x ), by ( R_{sy} = 1.732 ) ( ( R_y = \sqrt{2\mu - 1} ) ), obtain the ( A_y ) of line b'-c';</td>
</tr>
<tr>
<td>2) For triangular wave form, ( PGA \cdot T_p/PGV = 8 ) and ( PGV \cdot T_p/PGD = 3.43 ), the PGAs and PGDs are,</td>
<td>2) Divided the velocity part of elastic design spectrum, ( V_y ), by ( R_{vy} = \mu = 2 ), obtain ( V_y ) of line c'-a';</td>
</tr>
</tbody>
</table>
3) The amplifier factors of triangular wave are, $a_A=2.74$, $a_V=2.64$, $a_D=1.32$;
4) Value of $f'$ is obtained by divided value of $f$, $D_y$ by $R_y=2$, connect $f'$ and $e'$;
5) Points a' and a are coincident, connect a' and b';
6) For $T_n<0.0303$ s, let $A_y=PGA$.

The proposed modified design spectra considering forward directivity effect are illustrated in Figs. 5 and 6. Other near-fault damage effects (including fling-step effect) could be used in the same manner.

### Discussion and Conclusions

An innovative identification method for a pulse-like seismic record is proposed. According to the characteristics of the pulse, it is identified by REZR based on two key parameters, the ratio of relative short-time energy and relative short-time zero crossing rate. The pulse is directly identified without representing the ground motion records using any other wave formula. This procedure is simple, efficient. More pulse-like ground motions which have multiple velocity pulses and irregular pulse can be detected by the REZR. Then the quantitative parameters of characteristics of pulse wave motion are studied, such as period, $T_p$, and $PGV$. The regression of $\sigma_{ln(PGV)}$ and $\sigma_{ln(Tp)}$ are demonstrated to be a random variable following Normal distribution. Parameters $T_p$ and $PGV$ can be used to effectively normalize the elastic and inelastic response spectra of SDOF systems subjected to typical pulse model. Such normalization makes feasible the specification of normalized design spectra for near-fault ground motion excitations of different epicentral distance.
Acknowledgments

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