A MATHEMATICAL MODEL FOR GENERATING THE PULSE-FREE PART OF THE NEAR-FIELD EARTHQUAKES

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ABSTRACT

Based on the recorded data, it is understood that the near-field earthquakes are often accompanied by a large energy pulse at the beginning of those records, caused by the so-called "forward directivity". Shortcomings of the response spectra approach in describing the considerable demands induced by the dominant velocity pulse of the near field earthquakes in different structures, makes it inevitable using time-history analyses in such circumstances. Since these velocity pulses seem to be simple in time domain, various attempts have been made to find a mathematical representation for them that can simplify the analysis of building structures subjected to these type of earthquakes. On the other hand, the significance of the remaining part of the near field earthquake records after pulse extraction is yet to be determined. In this paper, the residual part of 91 near-fault earthquake records produced by Baker through extracting the velocity pulses from the original records, are considered. A closed form relation for the FFT of the residual part of the records is proposed with a number of parameters to be determined through regression analyses. The time domain realizations of the synthetic residual records are determined using inverse Fourier transform. Finally, the simulated earthquake records constructed from a combination of Maveroeidis and Papageorgiou's velocity pulses and the simulated residual records are compared with the original near field strong ground motions and necessary conclusions made.

Keywords: Velocity pulse, Pulse shape, Background Earthquake, Near-Fault Earthquakes

1. INTRODUCTION

The near-field earthquakes differentiate from the far-field strong ground motions in some key aspects. The velocity time histories of near-fault earthquakes contain pulses that form their unique behavior. In other words, a “near-fault earthquake” is an earthquake featured with a large energy pulse at the beginning of its record. These specific characteristics of near field earthquakes should raise the concern of the engineers in using the very simple and straight forward response-spectra method. These pulses are exclusive for the forward direction of wave propagation from the source that occurs in the fault-normal component of strong ground motion [1].

Obviously, performing dynamic time-history analysis with the regular far field earthquake records is not very common for the engineers due to the appealing ease of response spectra method and its sufficient accuracy for most of the design or retrofitting cases. However, that does not hold for the near-field type of earthquakes that lack the necessary database for different sites as well as their complex nature. Hence, for the time being, it seems inevitable to think of using dynamic time-history analysis for design of structures located in the vicinity of the faults. Also, one could observe the need for developing appropriate algorithms to generate site-specific near field synthetic records.

Various attempts made for defining a proper pulse form to represent the near-fault records have succeeded in certain aspects. The main importance of simulating a simple representative of a stochastic phenomena is its effect on reducing the required analysis time and consequently simplifying design procedure .Various studies have implied that the response of a structure subjected to these pulses can be correlated with the “form of pulse”, “pulse intensity’ and “ratio of system’s fundamental period to the dominant period of pulse”. In the last couple of decades, many efforts have been made to determine an efficient pulse form with not much success. Using Hall’s 3 pulses model, Alavi and Krawinkler investigated their suitability in reproduction of the recorded near-fault earthquakes’ response spectra [1]. Due to their simple form, these pulses were unable to capture the complicated characteristics of the near-fault earthquakes.

Somerville utilized splines to model the ground motion’s largest cycle with smooth curves[2]. Having compared with Alavi and Krawinkler’s model, Somerville realized that more half cycles should be included in the model for more complete description of these ground motions. Menun and Fu proposed a 5-parameter model whose parameters can be obtained through a nonlinear regression analysis [3]. However, other researchers like Zhu & Xin-Le believed that having a constant period and limited number of half cycles(4 cycles at most) for simulation may lead to unrealistic results for certain types of ground motions [4].

Maveroeidis and Papageorgiou have proposed the following 5 parameters model for ground velocity[5]:

$$v(t)=\begin{cases}\frac{A}{2}\{1+\cos(\frac{2\pi f_p}{\gamma}(t-t_0))\}\cos(2\pi f_p(t-t_0)+\theta) & t_0-\frac{\gamma}{2f_p}<t<t_0+\frac{\gamma}{2f_p}\\ 0 & otherwise\end{cases} \tag{1}$$

Where A, f_p, θ, γ *and* t_0 represent the pulse’s amplitude, dominant frequency, phase lag, zero crossing and envelope function’s peak time respectively. Figure 1 shows a schematic representation of Maveroeidis and Papageorgiou’s model.

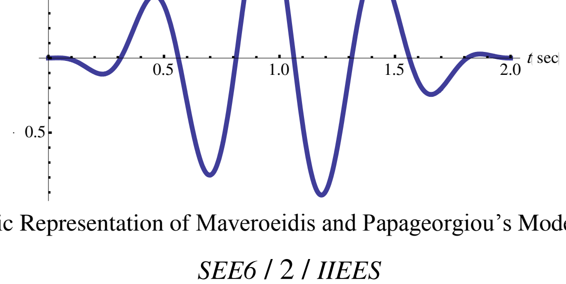

Figure 1. A Schematic Representation of Maveroeidis and Papageorgiou’s Model for velocity pulse[3]

Similar to Menun and Fu's model, this model also has difficulty in predicting the spectral values for short-period region of response spectra. Therefore, they used the "Specific Barrier Method" to produce the high frequency part of these earthquake records[5].

On the other hand, the effect of the pulse-free part of the near-field records after pulse extraction (residual records) is among the concerns, especially in high-frequency region. In this work, it is tried to alleviate those concerns by simulating the residual records whose importance has usually been ignored in recent researches. Also, Maveroeidis and Papageorgiou's model is adopted here to simulate the pulse-like signal of the near field earthquakes.

In the current study, all 91 near-fault records identified by Baker out of over 3500 NGR records of Berkeley University are considered [6]. All these records have PGV's greater than 30 cm/sec^2 and the moment magnitudes greater than 5.5. Response spectra method is used for determining the response of SDOF systems under seismic excitations.

2. SIMULATION OF RESIDUAL EARTHQUAKES

As it was mentioned earlier, there are two major components in any near-fault earthquakes, e.g. the pulse-like and the residual ground motions. Taking advantage of the comprehensive study carried out by Baker in capturing the main pulse of near-fault earthquakes [6], the resulting residual records presented in that work is used here for regression analyses and simulation of the residual part of near-fault earthquakes. Different mathematical functions with different number of parameters are considered in the regression analyses, using the Fourier amplitudes of 91 Baker's residual records. Figure 2 shows the Fourier amplitude of a residual record that is obtained by pulse extraction from the Imperial Valley-06 earthquake recorded at El Centro Differential Array station [6]. In the following, a number of possible approaches for simulation of the residual records are elaborated.

2.1. Kanaii-Tajimi's Model

The most referred method for synthetic record generation is Kanaii-Tajimi's model which is based on power spectral density of the records. In this model using a smooth curve fitted on the power spectrum of original records, the Fourier amplitudes of resulting record can be estimated. Combining the Fourier amplitudes and the random phase angles lead to the generation of synthetic records using an appropriate envelope function. However, it should be noted that the Kanaii-Tajimi's model, or its modified version include 3 or 5 unknown parameters that need to be determined through endless regression analysis for optimal determination of those parameters. Also, in many cases with more than 2 peaks in Fourier spectrum, as shown in Fig. 2, Kanaii-Tajimi's model is not very helpful.

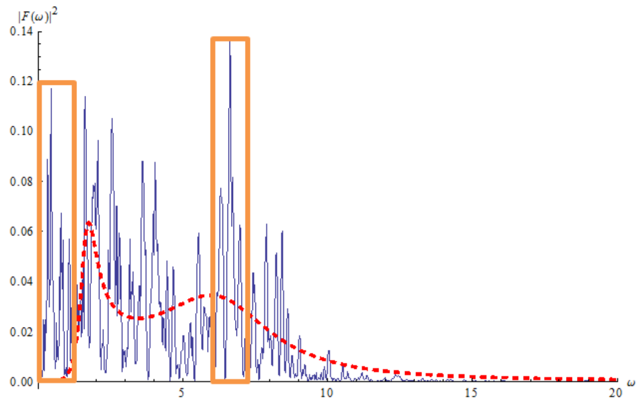

Figure 2. Fourier amplitude of a residual record of Imperial Valley-06 earthquake recorded at El Centro Differential Array station

2.2. New approach based on Rayleigh function

As it was previously mentioned, it is desired to develop a model which can predict the near-fault records even when few reliable recorded data is available. In this approach, increasing the number of parameters of the model is not always appealing because the more parameters used, the more regression equations needed with their own computational related error in the results. Therefore, it is more desirable to use a function possessing the same characteristics as those of Kanaii-Tajimi's with less number of parameters which is a key factor in reducing the analysis time. For that purpose, the following Rayleigh-Based Distribution (RBD) model is adopted here for the Fourier amplitude of the residual records:

$$|F(\omega)| = a\,\omega\, e^{-b\omega^2} \tag{2}$$

Where a and b are the model parameters and (ω) is the circular frequency. The resulting fitted curve is schematically shown in Figure 3, together with those generated using Kanaii-Tajimi and modified Kanai-Tajimi models.

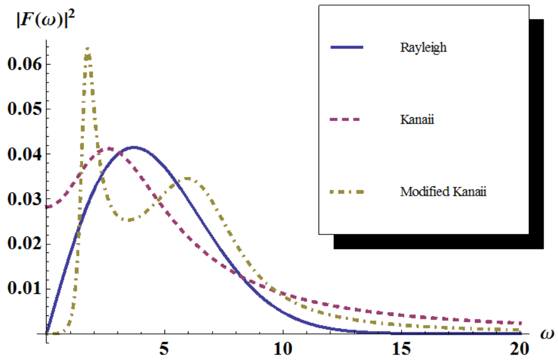

Figure 3. The comparison of Kanaii-Tajimi's model with the proposed RBD model

Compared to the Kanaii-Tajimi's model, the proposed RBD model has comparatively narrower frequency band and tends to zero for larger frequencies faster than the other models. Using the RBD model, the obtained Fourier amplitudes could be used to reconstruct the residual earthquake record using randomly generated phase angles and appropriate envelope function (Figure 4).

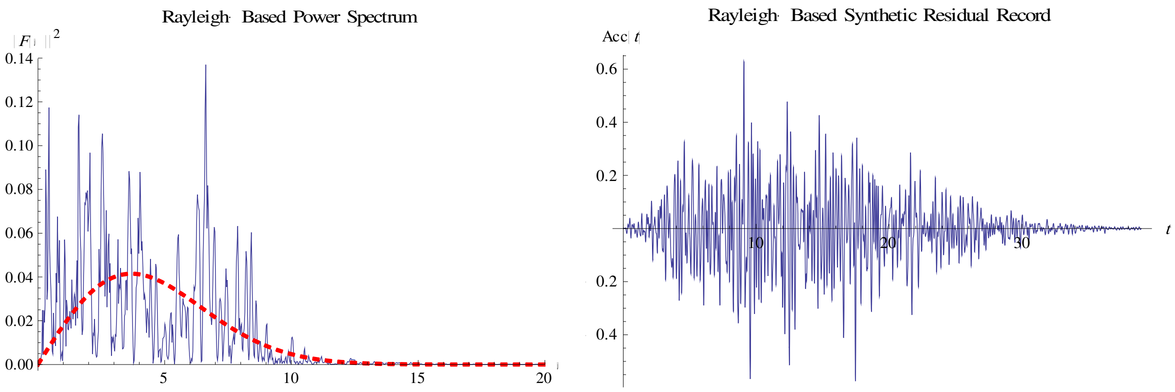

Figure 4. The RBD approximation of the power spectral Density and the resulted acceleration time history

2.3. Combining the residual earthquake with pulse-type ground motion

Having defined the Rayleigh-Based model for generating the residual records, the reproduced residual record should be combined with a pulse-like motion in order to obtain the synthetic near-field record. As it was mentioned before, Maveroeidis and Papageorgiou's model is used for generating the pulse-like part of the near-field records. In combining these two parts, and unlike the pulse-like ground motion that starts from t=0., the residual record is added to the pulse motion after a time delay and right after the pulse-like motion reaches its maximum amplitude (Figure 5). That is due to the fact that the velocity pulse caused by the forward directivity occurs at the beginning of the near fault records.

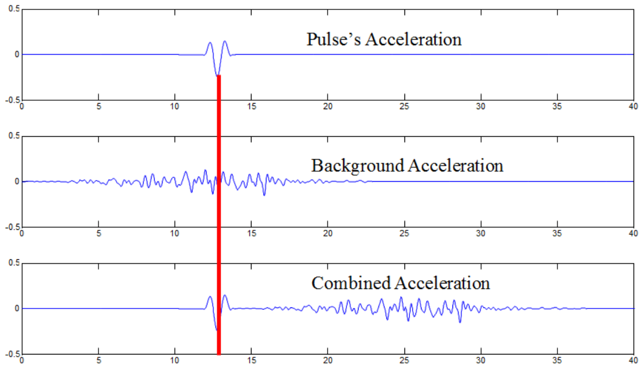

Figure 5. Procedure of combining pulse-free and pulse-type record

3. DEVELOPING REGRESSION RELATIONSHIPS FOR THE MODEL PARAMETERS

For cases where insufficient recorded data is available, regression relationships could be developed to correlate the important source characteristics including the site to source distance to the model's parameters. Having calculated the parameters of the introduced RBD model for all 91 records of Baker study, the efficiency of synthesized records were investigated through comparing their response spectrum with those of the original records. Given the model parameters for each record of database, the variations of these parameters can be described using the moment magnitude M_w and the epicentral distance R as two important characteristics of earthquakes. Therefore, the following function is considered for the regression analyses:

$$Ln(Z) = \alpha + \beta Ln(M_w) + \gamma Ln(R) \tag{3}$$

In which Z, M_w and R are the RBD model parameters(*a* or *b*), moment magnitude, and the site to source distance respectively. For the model parameter a, the unknown coefficients α , β and γ in Eq. (3) are obtained using a simple least square analysis as the followings,

$$a = -536 + 0.49Ln(R) + 312.2Ln(M_w) \tag{4}$$

It should be noted that only the earthquakes with R<50 Km were considered in derivation of Eq. 4. Due to good correlation between the RBD model parameters *a* and *b*, and instead of developing a similar relation for the model parameter *b*, the following relation is derived to determine the parameter *b*, as a function of parameter *a* using the Baker's near field earthquake database,

$$\log(b) = -2.0403 + 0.7157\log(a) \tag{5}$$

In derivation of these relations, the soil type was not considered as a parameter due to insufficient data.

4. GENERATION OF SYNTHETIC NEAR-FAULT RECORDS

In order to verify the efficiency of the proposed approach in generating the near-fault earthquakes, the reproduced synthetic records are compared with the original records of Baker's database. For the approach proposed in this work, the Maveroeidis and Papageorgiou's pulse model should be used to generate the velocity pulse for each of the Baker's near field records. Maveroeidis and Papageorgiou suggested the following relation to correlate the pulse's period (T_P) to the moment magnitude (M_W) of the earthquakes [3]:

$$Log(T_p) = -2.9 + 0.5M_w \quad (6)$$

However, since a different database has been used by Maveroeidis and Papageorgiou to generate this correlation function, it was necessary to develop a correlation function to properly relate the variations of pulse's period to the magnitude of earthquakes for current database (Figure 6).

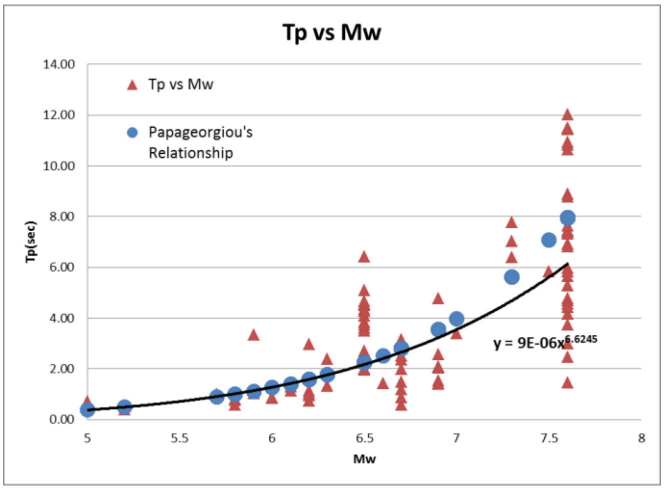

Figure 6. The Pulse Period(T_p) dependence on Moment Magnitude(M_w)

Therefore, the following equation is derived to estimate the pulse period of the Baker's database used in this study,

$$Log(T_p) = -5.048 + 6.625M_w \quad (7)$$

Finally, using Maveroeidis and Papageorgiou's pulse model given by Eq. 1 for simulating the pulse-like motion of the synthetic records, it is assumed that, $t_0 = \gamma / 2f_p$, so that the pulse-like motion starts at t = 0. Since the value of parameter γ is not known in advance, a sensitivity analysis is carried out to find its optimal value for having a better match between the simulated and the original ground motions. Also, the parameter ν was assumed to be 45°. Due to the existing difference between the Alavi and Krawinkler's database and Baker's earthquake records, a new regressive relation was developed to correlate the pulse's effective intensity and the earthquake parameters as the following (instead of using Alavi and Krawinkler's relation):

$$Ln(v_{eff}) = 3.18 + 0.19M_w - 0.19Ln(R) \quad (8)$$

Given the seismological information of Baker's database, a synthetic pulse-free residual record can now be generated.

Finally, combining the pulse-like motion and the residual record would result in the synthetic near field ground motions. As an example, Figs. 7 and 8 compare the response spectrum parameters of the combined synthetic and the original ones for two earthquake records. It seems that compared to the case of Fig. 7, better compliance with the original record is achieved for the case shown in Fig. 8.

4. CONCLUSIONS

Recent mathematical models to represent the near fault earthquakes lack the proper consideration of residual earthquake record. Ignoring the effect of residual earthquake that mainly affects the low period region of the response spectra is among the main concerns. In this study, an approach is proposed to model the residual records without using a complex random vibration based solution for the problem. Using Maveroeidis and Papageorgiou's model for the pulse-like part of the ground motion, a simplified two parameter model is proposed for the Fourier transform of the residual part of near-field records. Regression equations were developed relating the value of RBD model parameters to the earthquake important characteristics such as the earthquake magnitude and the site to source distance based on the

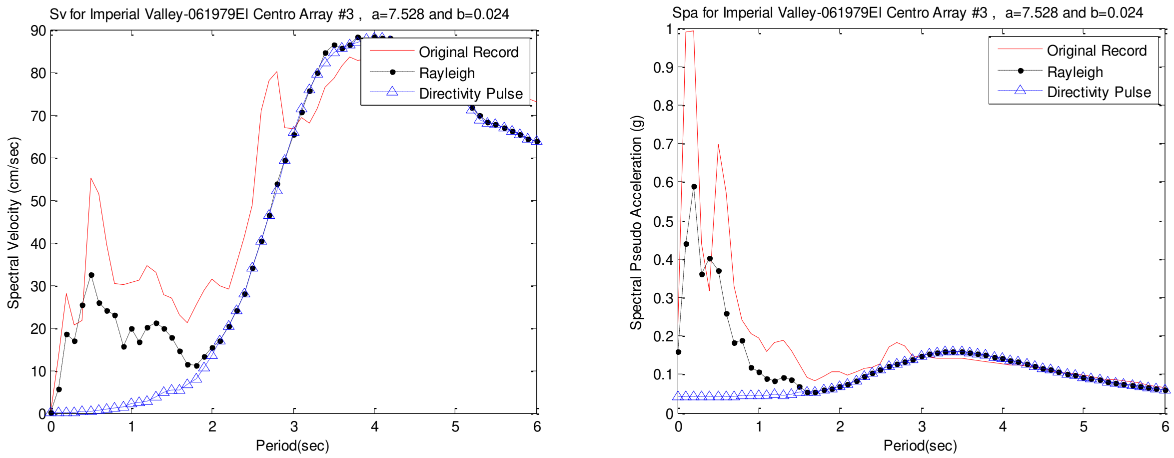

Figure 7: The Response Spectrum Parameters of the Simulated and Original Records for Imperial Valley-06 1979 Elcentro Array #3

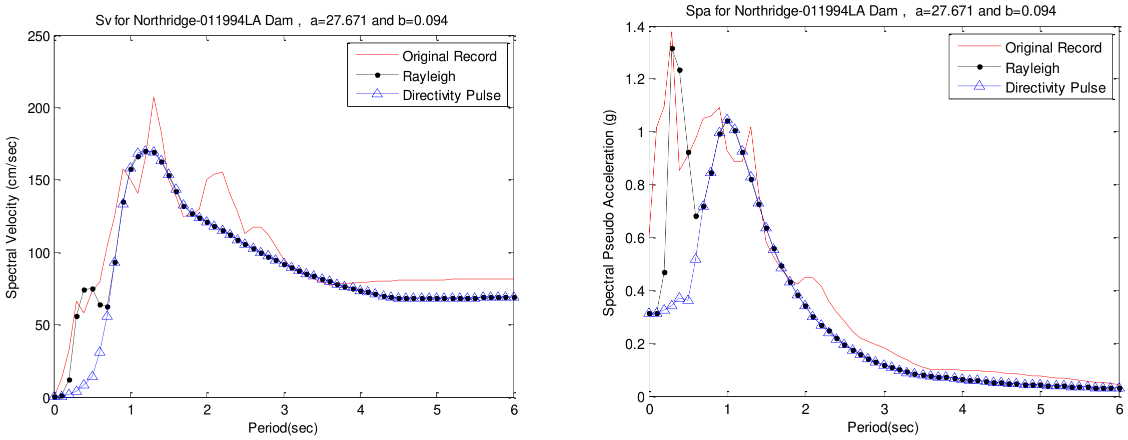

Figure 8. The Response Spectrum Parameters of the Simulated and Original Records for Northridge-01 1994 LA Dam

obtained values for Baker database. The suggested algorithm for simulating the near-fault earthquake records include the simulation of pulse-type ground motion using Maveroeidis and Papageorgiou's model and generation of residual earthquake using the proposed approach. Finally, the combination of these two parts leads to the simulated near field earthquake records. The obtained results indicate that using the proposed method, an acceptable match is achieved with the original records in low-period region of the response spectra.

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