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Parametric Closed-Form Formulation of Distinct Pulses in Strong Near-Field Ground Motions

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Abstract

Ground motions recorded in the near-fault zones exhibit unique physical characteristics different from far-field records. These differences are conspicuously evident in the configuration of accelerograms and their corresponding velocity-based as well as displacement-based time-histories. Particularly noteworthy are the variations observed in velocity time-histories, which require significant attention, especially in cases of intensive ground motions characterized by strong forward directivity effects. The presence of distinctive high-amplitude velocity pulses represents a vital aspect of these disparities. Numerous researchers have endeavored to develop closed-form formulas to accurately capture and explain these coherent pulses in velocity time-histories, as well as represent the medium to high-amplitude frequency domains of wave-type strong ground motions. These closed-form formulas have been prepared to provide mathematical expressions that can effectively model the unique features of strong near-fault ground motions. However, from the mathematical viewpoints achieving precise representations of the aforementioned pulses and the accompanying ground motion characteristics remains challenging. This paper aims to employ numerical modeling and analytical techniques to simulate the coherent velocity pulses, utilizing closed-form formulas and analytical approximations to closely replicate the features of the companion accelerograms accompanying the original earthquake records. Additionally, the calculation approach and processing of mathematical functions are concentrated on modeling and matching the companion parametric statements.

Keywords: Strong Ground Motion; Closed-Form Model; Near-Fault Zone; Forward Directivity Effect.

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1. Introduction

Generally, the ground motions which have been influenced by strong earthquakes in the near-fault zones, usually exhibit distinctive characteristics that differentiate them from far-field records. Notably, strong directivity effects resulting from fault rupture propagation direction emerge as prominent differentiating factors [1,2]. The investigation of the earthquake records featuring forward directivity effects has attracted significant attentions due to their distinct high-amplitude pulses with long periods which can be observed in velocity time-histories. These pulse-like features in the velocity time-histories possess the potential to induce significant damage in medium to high-rise structures. To have comprehensive data about the behavior and characteristics of pulse-like ground motions requires to establish and formulate the specialized modeling approaches and analytical techniques. Accurately capturing and simulating the pulse-like ground motions and their wavelet features is crucial. A fundamental step in the aforementioned analytical manner involves obtaining the velocity time-history from recorded ground motion accelerograms, followed by simulating and fitting coherent velocity pulses using closed-form solutions.

Several notable studies have contributed to this research field. Menun and Fu [3], Alavi et al. [4], Agrawal et al. [5], and Rodriguez Marek et al. [6] have presented outstanding researches that include closed-form solutions and analytical procedures for simulating and approximating companion records (i.e. aiming for the highest achievable similarity in time series) for strong ground motions. These companion records aim to capture the characteristics caused by the coherent velocity pulses. Among the available closed-from models proposed for approximating pulse-like motions, Mavroedis et al. [7] formulated a simple and applicable model. Additionally, Dickenson and Gavin [8] introduced a parametric closed-form formula based on the Gabor wavelet. Hong et al. [9] adopted some parametric statements for pulse-like components and furthermore, proposed a time- and frequency-dependent power spectral density model for the non-pulse-like components of ground motions.

To achieve an accurate representation of the high-amplitude and energetic compositions within the velocity time-history, the primary objective is to generate a companion record that faithfully captures the original free-field motion's energy release variation and frequency content. Consequently, a conventional approach for evaluating the simulated model generally involves a comparative analysis of the cumulative energy curves derived from the simulated model and the free-field record. Moreover, an essential step entails deriving the acceleration time-history from the simulated velocity time-history which can be accomplished through techniques such as the Fourier transform or numerical differentiation analysis. Notably, one of the most critical analytical procedures is the comparison between the recorded ground acceleration and the simulated time-history [10,11]. Additionally, employing analytical facilitations to approximate intensities offers a valuable method for refining the resemblance between the prepared artificial time-history and the recorded ground acceleration. A key factor in achieving accuracy lies in closely approximating the rate of change in the corresponding cumulative intensity curve. By doing so, the assigned wavelets and the evaluated frequency content and corresponding amplitudes progressively converge towards a more precise representation. The verification of the simulated acceleration time-history against the free-field record can be accomplished through the Fourier spectrum analysis, enabling a comparative assessment of the faithfully reproduced frequency content.

This paper presents a subjective and comprehensive compilation of the results obtained through a parametrized array of calculations and analytical processes. The primary focus revolves around the simulation of pulse-like components and the depiction of high-amplitude wavelets, as displayed in the velocity time-histories of an ensemble of the selective recorded near-fault ground motions. Adopting the closed-form solutions proposed by Menun and Fu [3] and Rodriguez Marek et al. [6], this study aims to expand and augment the application of these methodologies through the integration of analytical approaches.

2. Parametric Forms for Modeling of Coherent Velocity Pulses

In the context of proposing mathematical closed-form models, Menun and Fu [3] introduced a collection of compound relations comprising exponentials and trigonometric functions. These relations take the form of two sine-type closed-form wavelets, enabling the representation of four distinct analytical configurations. The considered formulas for the aforementioned wavelets are as follows:

$$\begin{aligned}
&\dot{u}(t) = V_p \exp\left[-n_1\left(\frac{3}{4}T_p - t + t_0\right)\right]\ \sin\left[\frac{2\pi}{T_p}\left(t - t_0\right)\right] && t_0 < t \le t_0 + \frac{3}{4}T_p \\
&\dot{u}(t) = V_p \exp\left[-n_2\left(t - t_0 - \frac{3}{4}T_p\right)\right]\ \sin\left[\frac{2\pi}{T_p}\left(t - t_0\right)\right] && t_0 + \frac{3}{4}T_p < t \le t_0 + 2T_p \\
&\dot{u}(t) = 0 && \text{otherwise}
\end{aligned} \tag{1}$$

Within these equations, the parameters V_p and T_p characterize the amplitude and period of the velocity pulse respectively, while t_0 defines the time at which the pulse starts. The shape parameters n_1 and n_2 can be set to 0.4 or 0.5, depending on the desired pulse shape.

Rodriguez Marek et al. [6] proposed a set of simple pulse waveforms represented by linear or trigonometric polynomials. These pulse waveforms are classified into three groups which are entitled as Basic Pulse (BP), Fling-Step Pulse (FSP), and Forward-Directivity Pulse (FDP). Each group consists of waveforms that can model a shock loading or gradual load cases. Considering the focus of the present paper which is concentrated on strong near-fault ground motions featuring forward directivity effects, the adoption of the following formulas can effectively capture the general pulse configurations. The peak acceleration (A) and pulse period (T_v) parameters within these formulas encapsulate the characteristics of pulse-type ground motions.

$$FDP1:\begin{cases}
\dot{u}(t) = At & 0 \le t < \dfrac{T_v}{4} \\
\dot{u}(t) = A\dfrac{T_v}{2} - At & \dfrac{T_v}{4} \le t < \dfrac{3T_v}{4} \\
\dot{u}(t) = -AT_v - At & \dfrac{3T_v}{4} \le t < T_v
\end{cases}\quad ; \quad FDP2:\begin{cases}
\dot{u}(t) = A\dfrac{T_v}{4\pi}\left(1 - \cos\left(\dfrac{4\pi t}{T_v}\right)\right) & 0 \le t < \dfrac{T_v}{4} \\
\dot{u}(t) = A\dfrac{T_v}{2\pi}\sin\left(\dfrac{2\pi t}{T_v}\right) & \dfrac{T_v}{4} \le t < \dfrac{3T_v}{4} \\
\dot{u}(t) = A\dfrac{T_v}{4\pi}\left(-1 + \cos\left(\dfrac{4\pi t}{T_v}\right)\right) & \dfrac{3T_v}{4} \le t < T_v
\end{cases} \tag{2}$$

3. The Selected Earthquake Motions

Strong near-fault ground motions can exhibit a distinctive characteristic of releasing significant amounts of energy within a short time domain. This evident effect results in a prominent jump-step visible in the plotted cumulative energy releasing process of the strong earthquake record. Additionally, this jump-step configuration corresponds to the emergence of high-amplitude pulses that are clearly observable in the ground velocity time-history. The primary criterion for selecting strong earthquake records in this study focused on the presence of coherent high-amplitude pulses in the corresponding velocity time-history, as well as considering the influence of site soil type [12,13]. Moreover, the subjective intention was to assemble a set of recorded ground motions closely aligned with sites classified as having dense soil and soft rock, and furthermore characterized by an average shear wave velocity in the soil layers ranging between 375 to 750 meters per second. Having these specifications, the selected site is categorized with the soil of type II, as considered by the

Iranian standard 2800 (the 4th edition) [14]. It is important to note that while the intention was to closely match these soil specifications, the selected ground motions may not precisely adhere to them. Table 1 provides a summary of the physical specifications corresponding to the time-history of both fault parallel (LN) and fault normal (TR) components of the selected records. Notably, all the ground motions in the selected ensemble are sourced from the PEER database [15].

Table 1. Physical specifications of the selected ground motions as well as encompassing both of the transverse (TR) and longitudinal (LN) components

Earthquake Record (distance from the causative fault)	Component	PGA (g)	PGV (cm/sec)	PGD (cm)	Arias Intensity (m/s)	Magnitude (Mw)
Northridge 1994 – Rinaldi (RRS - 7.1km)	LN	0.472	72.72	19.82	7.5	6.7
	TR	0.838	166.57	29.81		
Loma Prieta 1989 – Los Gatos (LGP - 6.1km)	LN	0.605	51.53	11.56	7.9	6.9
	TR	0.563	93.92	41.18		
Northridge 1994 – Sylmar (SYL - 6.4km)	LN	0.604	78.24	17.10	5.0	6.7
	TR	0.843	129.35	32.61		
Bam 2003 – Bam City (BAM - 1.0 km)	LN	0.620	59.25	20.78	8.0	6.6
	TR	0.780	121.48	37.33		
Cape Mendocino 1992 – Petrolia (PET - 9.5km)	LN	0.590	48.52	21.74	3.8	7.1
	TR	0.662	89.54	29.55		
Northridge 1994 – Sepulveda (SPV - 8.9km)	LN	0.939	75.95	15.12	7.0	6.7
	TR	0.752	84.48	18.69		

4. Closed-Form Modeling and Analytical Configuration

The existence of a predominant energetic component in the physical composition of strong near-fault ground motions which displays an evident abrupt surge in the cumulative energy release diagram, comprises a range of distinct high-amplitude wavelets and spikes which are augmented by the low to middle frequency bands. It is noteworthy that precise approximation of a coherent velocity pulse or multiple acceleration pulses cannot be necessarily achieved by simply modeling and fitting a few high-amplitude wavelets via utilizing compound trigonometric or exponential functions. Furthermore, attempting to model and fit a high-amplitude wavelet without considering local spikes within the separated target time windows may result in an inaccurate approximation, particularly in terms of frequency content. In this paper, a meticulous attention has been considered to covering the main energetic frequency range as well as ensuring fidelity to their corresponding equivalent wavelets and amplitudes, alongside taking an efficient energy release process.

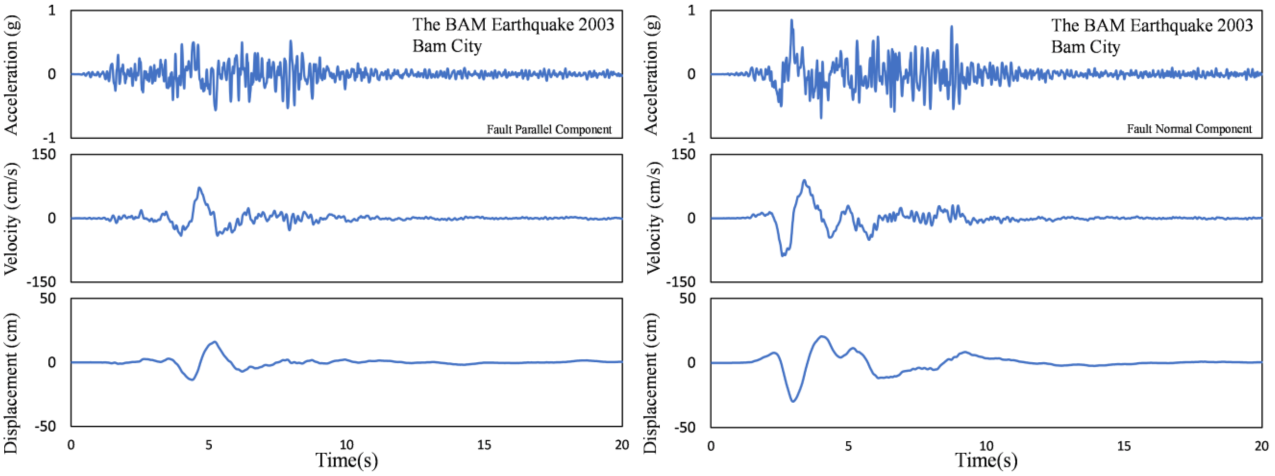


Figure 1. The recorded ground acceleration as well as velocity and displacement time-histories corresponding to the horizontal LN and TR components of the main shock related to the Bam Earthquake 2003.

Fig. 1 displays the recorded ground acceleration along with the velocity, and displacement time-histories corresponding to the fault parallel (LN) and fault normal (TR) components of the main shock of the Bam Earthquake 2003. The summarized specifications of this earthquake record can be found in Table 1. It is important to note that all ground motions in the selected ensemble display pulse-like characteristics. To obtain the velocity time-history, a numerical integration process has been carried out on the recorded ground acceleration and the same procedure has been also performed on the computed ground velocity to obtain the related displacement array.

The approximation of the velocity time-history in this study has been conducted based on the analytical closed-form models proposed by references [3] and [6]. Accordingly, the simulation of high-amplitude wavelets can be accomplished by employing Eqs. (1) and performing an analytical implementation of the FDP2 Pulse group of Eqs. (2). Additionally, for simulating the wavelets and spikes with distinctive extremum shapes, Eqs. (1) and the FDP1 Pulse in Eqs. (2) are applicable. Furthermore, since Eqs. (1) employ trigonometric statements, each simulated wavelet or pulse feature carries a specific frequency. On the other hand, the FDP1 Pulse in Eqs. (2) encompasses a number of frequencies that can be decomposed through the implementation of Fourier transform analysis. The utilization of Eqs. (1), proposed by Menun and Fu [3], generates a spectrum of pseudo-sinusoidal arrays corresponding to an assumed pulse period, as it combines trigonometric and exponential functions.

It should be noted that through performing the aforementioned compositions and analyses with respect to the target time windows and the assigned orient axis, the resulted wave-like features with a tuned increasing-decreasing configuration, progressively achieve heightened accuracy. Subsequently, shifting the assigned orient axis in the time window under study would evidently facilitate the attainment of the desired pulse or spike shape characterized by the real record and its distinct peaks. The applicability of Eqs. (1) extends across a broader range within the time window under study, encompassing a variety of increasingly efficient wavelets with the assigned characteristics. Consequently, the closed-form solution proposed in the reference [6] can be specifically employed for modeling long-period wavelets with triangular shapes. And, the implementation of the closed-form model proposed in the reference [3] may indicate some analytical inefficiencies for processing such wavelets.

The BAM record displays a maximum ground velocity of 121.48 cm/s and demonstrates pulse-like motion characteristics. Fig. 2 shows a velocity time window ranging between the axes of second 2 until 4 related to the TR component and its corresponding acceleration time-history. This time window corresponds to a significant energetic part of the distinct coherent velocity pulse. In Fig. 2, there is a velocity pulse-like composition with an absolute extremum higher than 50 cm/s in the negative domain, starting after the second 2 and continuing until roughly after the second 3 throughout the full time-history. This pulse-like composition consists of more than two local segmented time domains which collectively contribute to its distinctive physical characteristics. The approximation of this mentioned pulse-type composition was carried out by adopting Eqs. (1). The corresponding acceleration time-history of each approximation is also depicted alongside the velocity time-history as well as showing the resultant computed acceleration. Moreover, main specifications and parameters used to generate each simulation in the velocity time-history and its corresponding acceleration values are illustrated in each segmented time domain, too.

As seen in Fig. 2a, two-step simulation of the velocity pulse-like composition is depicted. Although the two simulated models have the same assessed frequency, however breaking down of the analytical composition into two separate pulse-type configurations can potentially affect the modeling precision. This is especially evident in terms of the assessed frequency content. Moreover, evaluating the mentioned composition with two time-window sets results in the simulation of energetic high-amplitudes spikes in the ground acceleration time-history, as indicated by the arrows (Fig. 2a). On the other hand, Fig. 2b shows the same velocity pulse which has been modeled in one analytical step, resulting in the failure to capture acceleration spikes. In the process of selecting an appropriate time window, the conceptual aim is basically to encompass the entire coherent velocity pulse, and furthermore it is needed to extend the subject further to include a range of high-amplitude spikes. This manner is important in conjunction with predicting the amount of kinetic energy which is released during the intensive strong ground motions. The main objective behind approximating the velocity time-history is twofold. The first item is to accurately represent and tune the considered closed-form wavelets. Also, the second item is to get an appropriate evaluation of variation rates related to the kinetic energy releasing diagram due to a strong earthquake record.

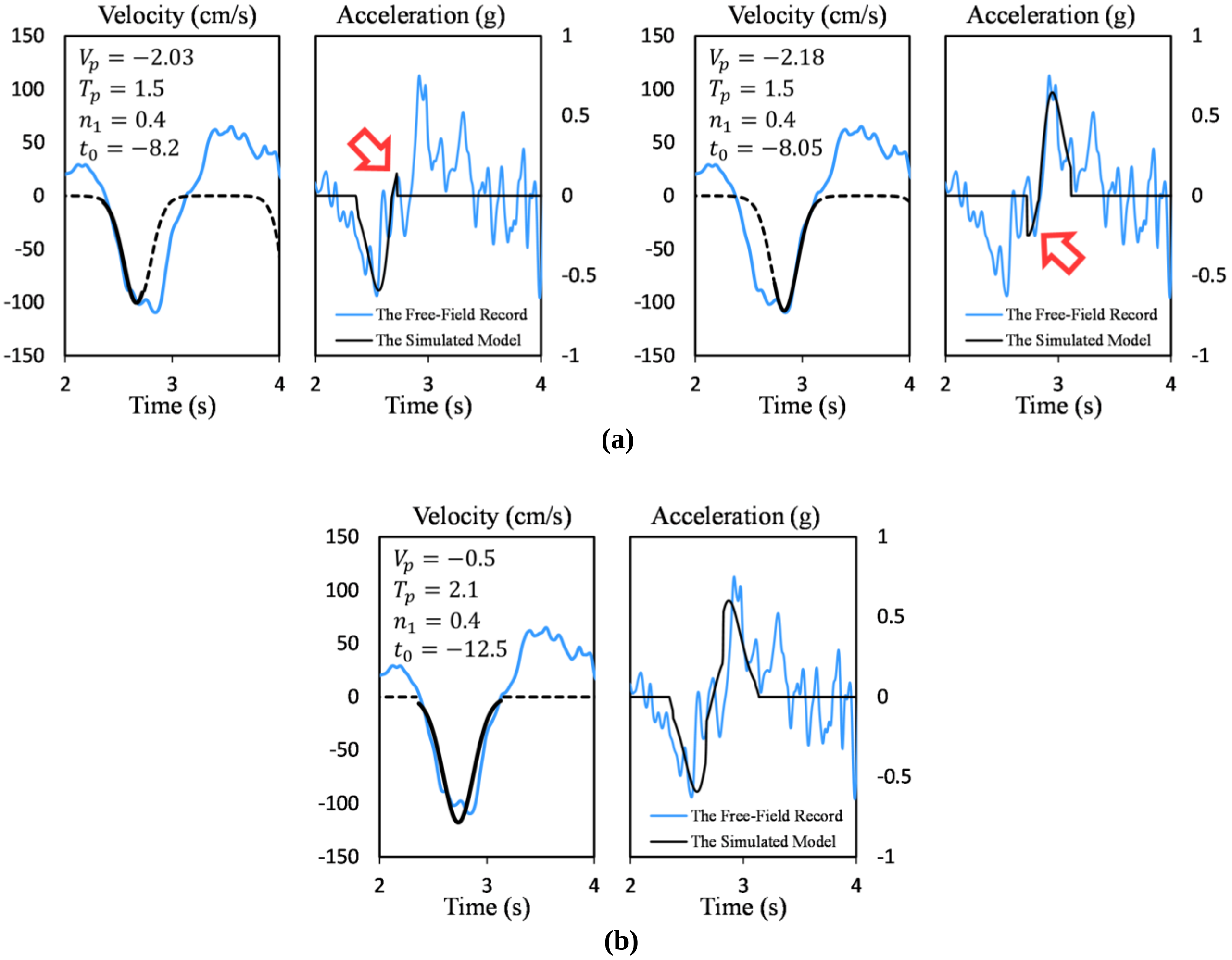
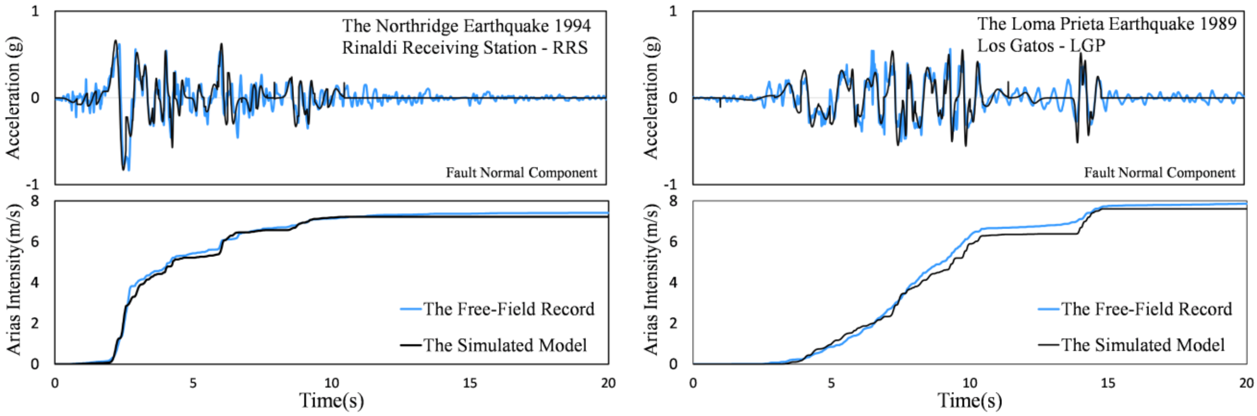


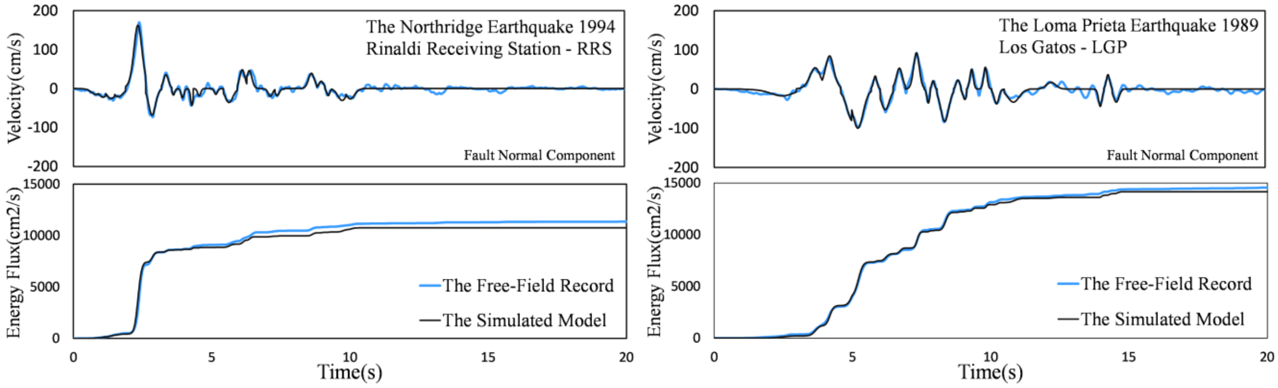
Figure 2. Comparison of the assigned approaches for velocity pulse modeling: (a) The velocity pulse is assessed and modeled in two steps through different time windows and effectively capturing the spikes in the acceleration plot (depicted with arrows); (b) The entire velocity pulse is assessed in one step with neglecting its local wavelets and failing to capture the spikes in the acceleration plot.

It should be noted that in the assessment and synchronizing of the kinetic energy releasing due to closed-form modeling of directivity process, there are two crucial subjects which must be considered. These mentioned subjects are generally entitled as "coverage variation of the energy being released from the record" and "obtaining the resemblance to the rate of energy release by the record". In this respect, Figures 3 and 4 show the results of modeling and fitting the acceleration and velocity time-histories related to the TR component of the selected earthquake records. Notably, in this modeling process, the parametric framework proposed by Menun and Fu [3] carries significant analytical weight and contributes extensively to the representation of the velocity time-histories.

Beneath each velocity time-history, the cumulative release manner of seismic energy related to an earthquake record has been compared with the one due to the simulated model. This is based on ensuring that the analytical close-form modeling covers at least 95% of cumulative amounts of kinetic energy released by the considered free-field earthquake record. During the process of selecting and adjusting parameters of the assigned closed-form models, a meticulous approach was followed to approximate the considered wavelets and cover a broader range of velocity components in the related time-history. Notably, the assigned period of each considered wavelet should be varied appropriately in the different time-histories under study. Furthermore, the implementation of the approved closed-form functions that satisfy mathematical differentiability and monotonicity conditions was essential. This is a particular analytical subject especially when the modeling process of pulse-type ground motions featuring multiple high-amplitude wavelets.

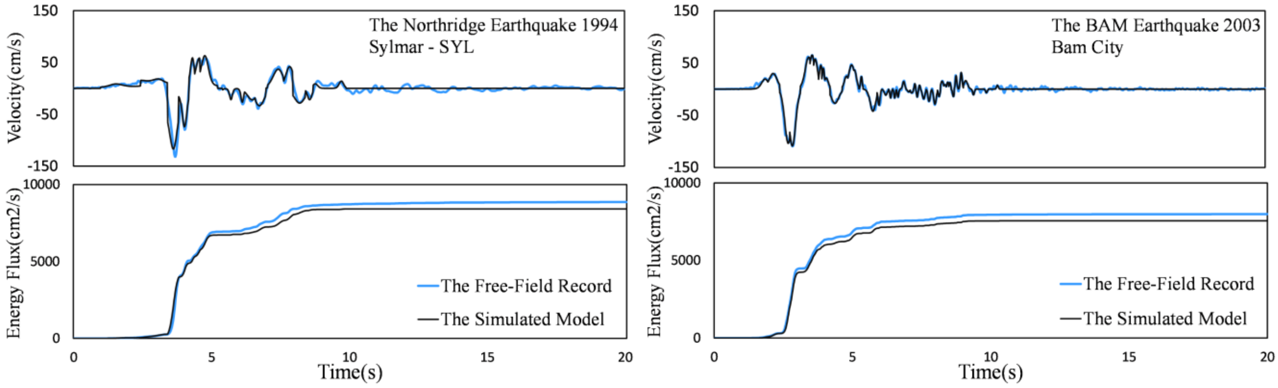


(a) to be continued



(b) to be continued

Figure 3. Assigned closed-form modeling and fitted acceleration and velocity time histories related to the TR component of the RRS 1994 and LGP 1989 records: (a) The computed ground acceleration and corresponding Arias intensity; (b) The assessed ground velocity and related energy flux.



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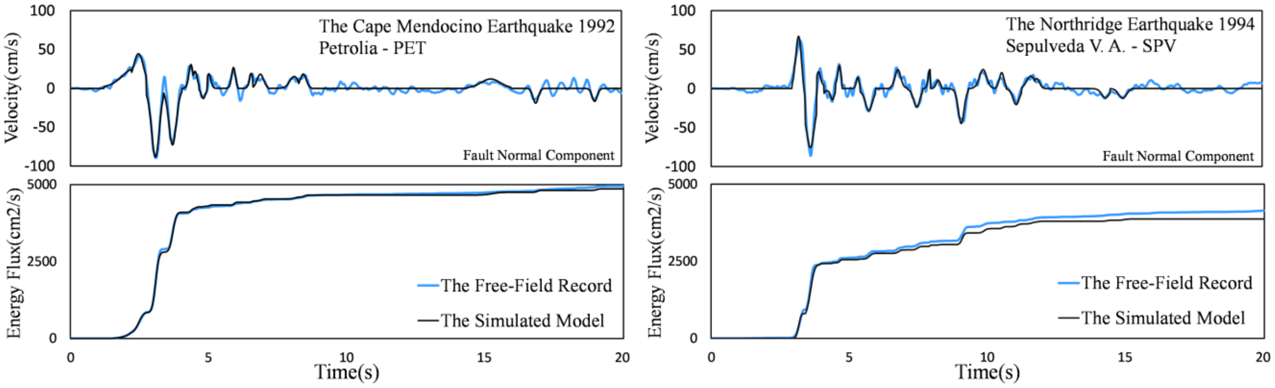
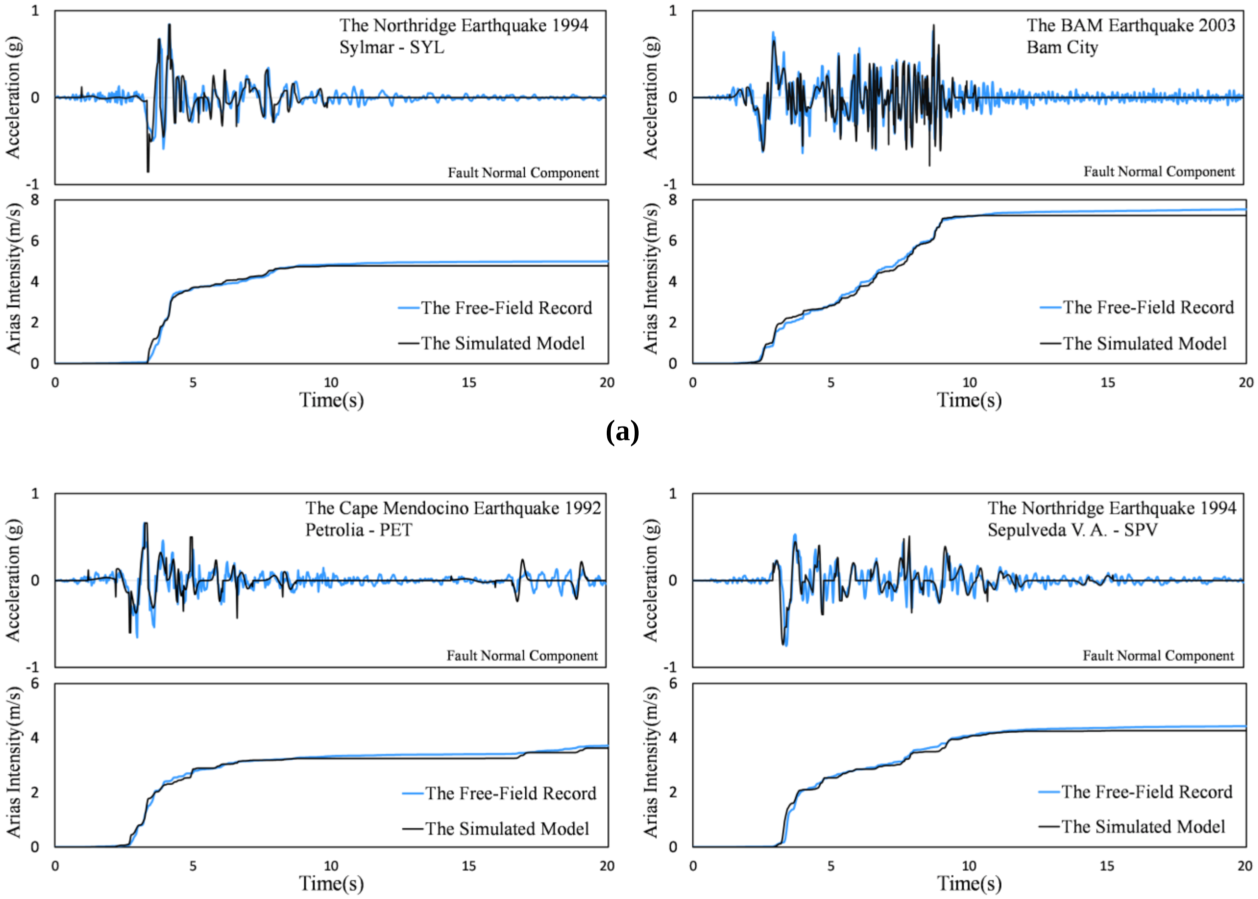


(b)

Figure 4. Assigned closed-form modeling and fitted velocity time-history related to the TR component as well as cumulative variation of corresponding released kinetic energy for the selected earthquake records: (a) the SYL 1994 and BAM 2003 records; (b) the PET 1992 and SPV 1994 records.



(a)

(b)

Figure 5. Comparison of the acceleration time histories related to the TR component of free-field earthquake records and closed-form simulated tremor as well as the corresponding Arias intensities: (a) the SYL 1994 and BAM 2003 records; (b) the PET 1992 and SPV 1994 records.

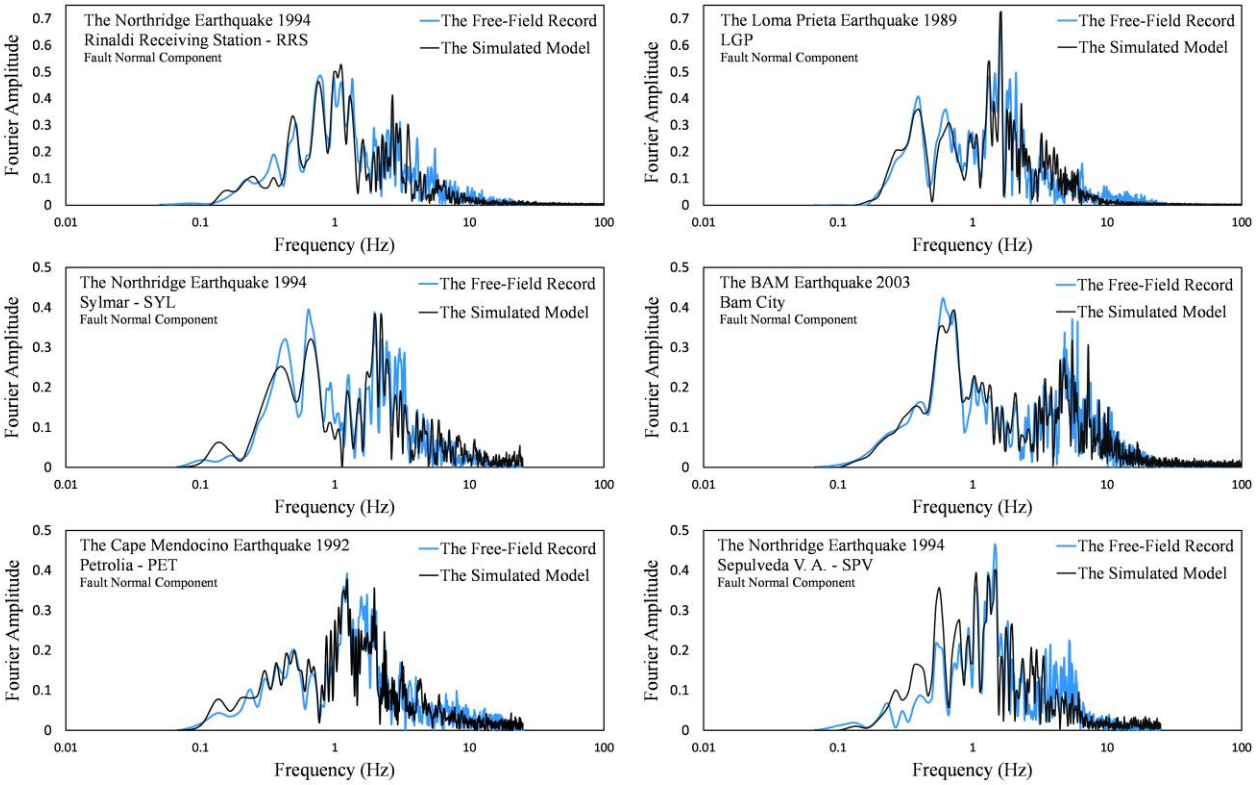


Figure 6. Fourier spectrum comparison for the TR component of the selected records and corresponding closed-from representations.

An essential aspect of precision monitoring and verification of the prepared closed-form motions involved comparing the obtained acceleration time-history with the one corresponding to free-field records. For this purpose, numerical differentiation was performed to obtain acceleration time-history from the closed-form ground velocity. Moreover, the Arias intensity as a well-established strength measure quantifying the intensity of ground shakings was assessed for the analytical comparisons.

Fig. 5 presents the comparison between the TR component of the free-field recorded ground accelerations and their closed-form illustration as companion artificial motions, along with the corresponding Arias intensities. The analytical process involved utilizing closed-form statements and adopting computational facilitations to ensure that the parametric mathematical model approximates the free-field record. This is numerically prepared so that the amplitude and corresponding Arias intensity covers at least 95% of the companion parameters related to the considered free-field earthquake record.

Additionally, in order to assess the numerical precision of the approximated frequency content, a Fourier spectrum analysis was performed too. Fig. 6 illustrates the Fourier spectrum comparison due to the TR component of the selected records and their closed-form companion motions. The special intention is to approximate the amplitudes and temporal arguments of the assigned wavelets in low to mid-range frequency domain for the distinct pulse-like features as well as a number of companion energetic spikes.

5. Conclusion

In this study, numerical efficiency of two well-known mathematical closed-form models for approximating coherent velocity pulses in near-fault ground motions was investigated. The both simulation processes were implemented on six strong near-fault motions to compare the closed-form companion models with free-field earthquake records. The obtained results demonstrate that adopting appropriate parametric statements and analytical facilitations would conclude the relatively accurate approximations of near-field pulse-like motions. A basic criterion in this process is determining the appropriate time windows for the simulation and adjusting model parameters to cover at least 95% of the cumulative kinetic energy released by the corresponding free-field record. Furthermore, similar adjustments can be applied to the assigned intensity measures and approaching the more accurate approximations in conjunction with the frequency content assessment and any further enhancing related to the conceptual fidelity of the closed-form simulations.

It should be noted that in the comparison between the companion closed-form motions and free-field earthquake records, the findings indicate a favorable agreement. This manner denotes the potential effectiveness of the closed-form approach in achieving accurate representations for the pulse-like ground motions. Moreover, the Fourier spectrum analysis would also support the accuracy of the assigned closed-form method for indicating nearly precise representations of pulse-like earthquake records.

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