I S A V

Journal of Theoretical and Applied Vibration and Acoustics

journal homepage: http://tava.isav.ir

Analytical synthesis of pulse-like strong near-fault ground motions through a parametric closed-form approach

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Research Article

ARTICLE INFO

Article history:
Received 9 May 2024

Received in revised form
24 February 2025

Accepted 24 April 2025

Available online 2 September 2025

Keywords:
Strong ground motion

Closed-form model

Near-fault zone

Forward directivity effect

ABSTRACT

Near faults, recorded ground motions exhibit unique physical characteristics, different from those observed in far-field regions. These disparities are particularly evident in the configuration of accelerograms and their corresponding velocity- and displacement-based time-histories. The pulse structures observed in velocity time-histories characterized by an abrupt surge in the rate of energy release, especially in intensive ground motions with strong forward directivity effects, demand scrutiny. Many researchers have sought to develop closed-form formulas to accurately capture and explain these coherent pulses, as well as represent the medium- to high-amplitude frequency domains of 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. Existing approaches typically rely on parametric formulations validated primarily through root-mean-square error minimization between modeled and recorded velocity time-histories. However, this paper presents a comprehensive analytical framework that implements systematic modeling and validation steps focused on capturing the essential physical characteristics of pulse-like near-fault ground motions critical for engineering applications. Adopting a set of closed-form formulas, this study replicates the key features of six strong near-fault earthquake records, with the methodology encompassing multiple validation criteria, including energy variation and displacement time-history profiles. The analytical models successfully captured at least 95% of the cumulative kinetic energy released during each record. These models demonstrate promising results in both rate of change and peak accuracy of displacement time-

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http://dx.doi.org/10.22064/tava.2025.2028274.1239

histories and effectively represent the main energetic frequency content throughout the analyzed time windows.

1. Introduction

Seismic activities recorded close to faults often showcase unique attributes that set them apart from far-field records. Especially noticeable are the prominent differentiating factors arising from strong directivity effects caused by the direction of fault rupture propagation [1, 2]. The scrutiny of earthquake records characterized by forward directivity effects has become a focal point, given their notable high-amplitude pulses observed in velocity time-histories, distinguished by extended periods. These pulse-like features in the velocity time-histories possess the potential to induce significant damage in medium to high-rise structures. Alavi and Krawinkler [3] investigated the response of elastic and inelastic frame structures to near-fault ground motions. Their study revealed period-dependent variations in the seismic behavior and led to regression equations predicting base shear strength and reducing ductility demands, advancing knowledge of near-fault seismic effects. Developing specialized modeling approaches and analytical techniques is essential for comprehensive understanding of the behavior and characteristics of pulse-like ground motions. Accurately capturing and simulating these motions, along with their wavelet features, is of paramount importance. 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. In this regard, several notable studies have been conducted. Baker [4] developed a wavelet-based technique to quantitatively identify and parameterize prominent and coherent velocity pulses in the time-history of near-fault ground motions. Applying this approach to the PEER NGA database [5] revealed 91 recordings exhibiting definitive pulses, likely caused by forward directivity effects. Evaluating the physical characteristics of directivity pulses allows prediction of the general occurrence conditions and corresponding probabilities based on the source faulting parameters. Sharbati et al. [6] advanced a novel method for detecting and extracting near-field velocity pulses via the Asymmetric Gaussian Chirplet Model (AGCM), addressing limitations of prior approaches such as underestimation of sharp peaks, overestimation of smooth ones, and reliance on singular dominant frequencies. Liu [7] evaluated pulse-like ground motions, emphasizing their deleterious impact on building structures. Considering wavelet-based recognition strategies, Liu introduced an innovative method based on Hilbert-Huang Transform (HHT), discovering remarkably greater numbers of near-fault velocity pulses relative to preceding techniques.

Notable research conducted by Menun and Fu [8], Agrawal et al. [9], Li and Zhu [10], and Xie et al. [11] have explored closed-form solutions and analytical methods. Their work aims to establish formulas for approximating velocity pulses, laying the foundation for achieving maximum similarity in time series. The objective of generating companion time series is to capture the characteristics induced by the coherent velocity pulses. Among the available closed-form models proposed for approximating pulse-like motions, Mavroeidis and Papageorgiou [12] formulated a simple and applicable model. Additionally, Dickenson and Gavin [13] introduced a parametric closed-form formula based on the Gabor wavelet. Zhou and Li [14] established a stochastic simulation method for velocity pulses centered around Gabor wavelet modeling and probabilistic correlation analysis. Liu et al. [15] adopted some parametric statements for pulse-like components.

They proposed a time- and frequency-dependent power spectral density model for the non-pulse-like components of ground motions. Ezzodin et al. [16] put forth a wavelet-based model that generates pulse-like artificial closed-form models containing fling-step and double-sided features, leveraging a bespoke polynomial bell-shaped function to delineate non-pulse aspects. Their results align closely with actual data, enabling development of predictive links connecting critical pulse parameters with earthquake/site attributes. Peng et al. [17] proposed an efficient method for stochastic simulation of coherent velocity pulses using multivariate copula modeling to represent the probabilistic correlation between analytical parameters of the Gabor wavelet model.

The primary goal is to generate a companion record that captures the original free-field motion's energy release variation and frequency content, aiming for an accurate representation of the high-amplitude and energetic compositions within the velocity time-history. By doing so, a conventional approach for evaluating the simulated model typically includes a comparative analysis of the cumulative energy curves derived from the fitted closed-form statement and the basic free-field record. For this purpose, a crucial step involves deriving the acceleration time-history from the simulated velocity time-history, which can be achieved through techniques such as the Fourier Transform or numerical differentiation analysis. It is worth noting that one of the most paramount analytical procedures is comparing the recorded ground acceleration with the corresponding simulated time-history. Furthermore, employing analytical facilitations to approximate intensities provides a valuable method for refining the resemblance between the prepared artificial time-history and the recorded ground acceleration. To attain the desired precision, it is crucial to closely approximate 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 basic free-field record can be accomplished through the Fourier spectrum analysis, enabling a comparative assessment of the reproduced frequency content. To ensure a comprehensive evaluation of the simulated companion motions, it is imperative to consider additional factors beyond the energy release process and frequency content. Incorporating comparisons of displacement time-histories offers valuable insights into the balance between positive and negative domains within the simulated velocity time-history. This nuanced analysis can illuminate potential discrepancies and guide further refinement of the modeling and fitting of closed-form simulations. Thus, by integrating assessments of displacement time-histories alongside energy and frequency considerations, the accuracy and fidelity of the simulated representations can be further enhanced.

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 selected near-fault ground motions. Adopting the closed-form solutions proposed by Menun and Fu [8] and Xie et al. [11], this study aims to expand and augment the application of these methodologies through the integration of analytical approaches.

2. Selection of parametric models for the representation of pulse structures

It should be noted that to propose mathematical closed-form models, Menun and Fu [8] introduced a series of compound relations consisting of exponentials and trigonometric functions. These relations emerge as two sine-type closed-form wavelets, enabling the depiction of efficient, distinct analytical configurations. The formulations for these wavelets are outlined below:

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

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 generally set to 0.4 or 0.5, depending on the desired pulse shape.

Xie et al. [11] proposed a set of simple pulse waveforms represented by linear or trigonometric polynomials. These pulse waveforms are classified into three groups, which are entitled Basic Pulse (BP), Fling-Step Pulse (FSP), and Forward-Directivity Pulse (FDP). Each group consists of waveforms that can model shock loading or gradual loading 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.

$$FDP1\text{:}\left\{\begin{array}{ll}
\dot{u}(t) = At & 0 \le t < \dfrac{T_v}{4} \\
\dot{u}(t) = A\dfrac{T_v}{2} - At & \dfrac{T_v}{4} \le t < \dfrac{3T_v}{4} \\
\dot{u}(t) = -AT_v - At & \dfrac{3T_v}{4} \le t < T_v
\end{array}\right\}$$

$$FDP2\text{:}\left\{\begin{array}{ll}
\dot{u}(t) = A\dfrac{T_v}{4\pi}\left(1 - cos\left(\dfrac{4\pi t}{T_v}\right)\right) & 0 \le t < \dfrac{T_v}{4} \\
\dot{u}(t) = A\dfrac{T_v}{2\pi} sin\left(\dfrac{2\pi t}{T_v}\right) & \dfrac{T_v}{4} \le t < \dfrac{3T_v}{4} \\
\dot{u}(t) = A\dfrac{T_v}{4\pi}\left(-1 + cos\left(\dfrac{4\pi t}{T_v}\right)\right) & \dfrac{3T_v}{4} \le t < T_v
\end{array}\right\} \tag{2}$$

The selection of Menun and Fu [8] and Xie et al. [11] formulas stems from their efficacy in capturing the extreme characteristics of energetic pulses within velocity time-histories. These parametric combinations offer a robust framework for modeling pulse-like ground motions due to several technical reasons. Firstly, the inclusion of exponentials in these formulations provides a versatile means to describe the rapid rise and fall of velocity pulses, facilitating precise representation of the transient behavior exhibited by strong ground motions. Moreover, the integration of trigonometric functions enables the modeling of oscillatory phenomena, essential for accurately depicting the frequency content and wavelet features present in velocity time-histories. Additionally, the applicability and ease of use of these formulas make them well-suited for seismic analysis tasks, allowing researchers to quickly and effectively model complex ground motion scenarios. Furthermore, the behavior of trigonometric functions under differentiation and integration ensures that these formulations maintain their analytical tractability and fidelity, even when subjected to rigorous mathematical operations. Overall, the combination of these factors renders the formulations proposed by Menun and Fu [8] and Xie et al. [11] highly effective for capturing the dynamic behavior of pulse-like ground motions in near-fault zones.

3. The selected ensemble of strong ground motions

Near-fault ground motions, renowned for their directivity-related characteristics, manifest a unique feature in the cumulative energy release plot of earthquake records, i.e., a notable jump-step. This distinctive pattern aligns with the appearance of high-amplitude pulses discernible in ground velocity time histories. 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, and also considered the influence of site soil type. 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 characterized by an average shear wave velocity in the soil layers ranging from 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 (4^{th} edition) [18], which is particularly significant for two key reasons: First, these soil conditions are predominantly encountered across Iran's seismically active regions, making the findings directly applicable to practical engineering scenarios. Second, and more importantly, these soil conditions facilitate the clear manifestation of pulse-type characteristics in ground motions, particularly the concentrated energy release pattern that is crucial for this study. 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. The focus on this soil type is especially relevant for mid to high-rise structures, which are particularly susceptible to the effects of pulse-like ground motions, thus making this selection criterion aligned with the engineering objectives of this research. 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 earthquake records. Notably, all the ground motions in the selected ensemble are sourced from the PEER database [5].

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

Earthquake record (station code name - Rrup)	Component	PGA (g)	PGV (cm/s)	PGD (cm)	Magnitude (Mw)
Northridge 1994 – Rinaldi Receiving Station (RRS – 6.5km)	LN	0.472	72.72	19.82	6.7
	TR	0.838	166.57	29.81	
Loma Prieta 1989 – – Los Gatos Presentation Center (LGP – 6.1km)	LN	0.605	51.53	11.56	6.9
	TR	0.563	93.92	41.18	
Northridge 1994 – Sylmar – Olive view medical center (SYL – 5.3km)	LN	0.604	78.24	17.10	6.7
	TR	0.843	129.35	32.61	
Bam 2003 – Bam City (BAM - 1.7 km)	LN	0.620	59.25	20.78	6.6
	TR	0.780	121.48	37.33	
Cape Mendocino 1992 – Petrolia (PET - 9.5km)	LN	0.590	48.52	21.74	7.0
	TR	0.662	89.54	29.55	
Northridge 1994 – Sepulveda VA medical center (SPV - 8.4km)	LN	0.939	75.95	15.12	6.7
	TR	0.752	84.48	18.69	

4. Analytical formulation and simulation of directivity pulses

The distinctive nature of intense near-fault ground motions is characterized by a pronounced surge in energy release, featuring an array of high-amplitude wavelets and spikes across low to middle frequency bands. However, accurately representing coherent velocity or acceleration pulses entails more than merely modeling high-amplitude wavelets using 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, careful attention was paid 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 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. The velocity time-history was derived through numerical integration of the recorded ground acceleration, while a similar procedure was applied to the computed ground velocity to obtain the corresponding displacement array.

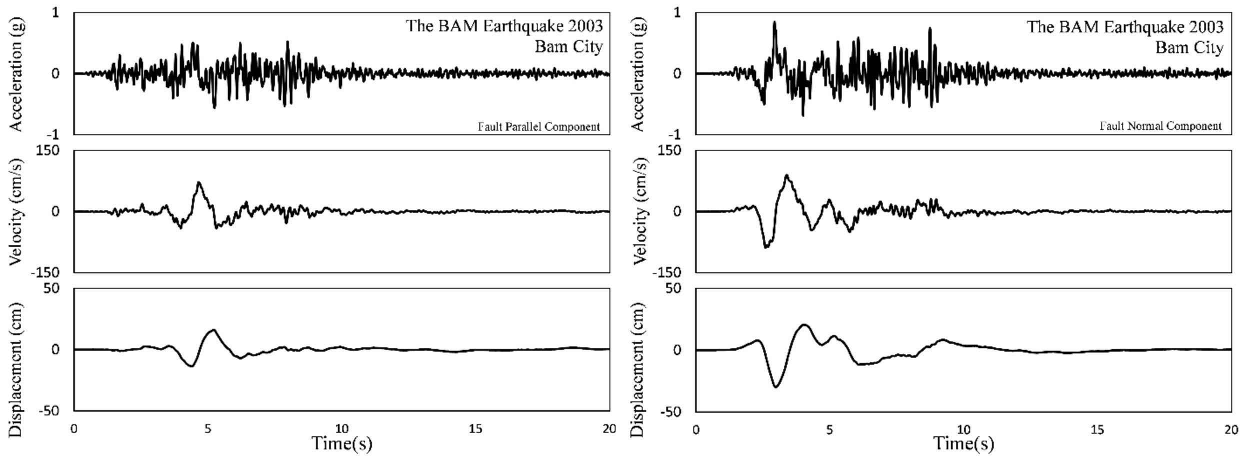
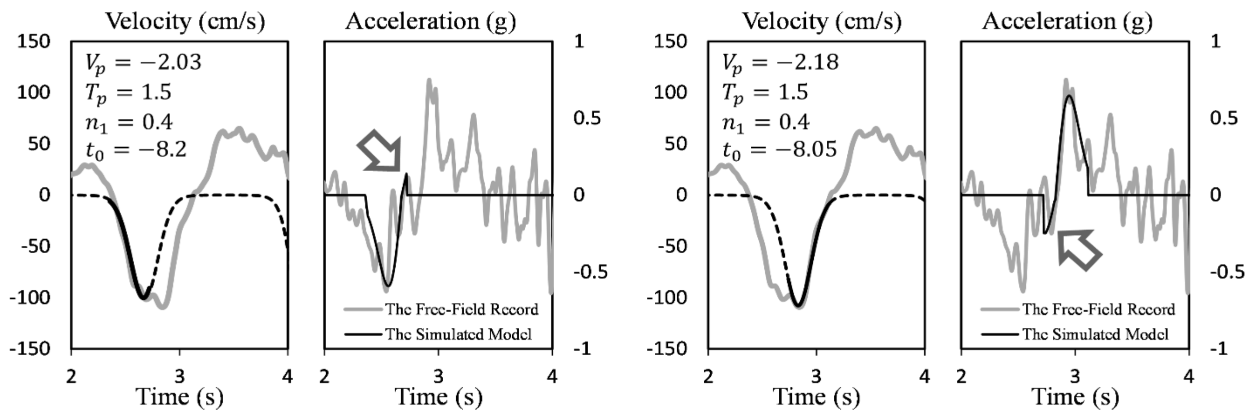


Fig. 1. The recorded ground acceleration as well as velocity and displacement time-histories corresponding to the horizontal LN and TR components of the main shock related to the Bam Earthquake 2003. This data serves as the baseline for subsequent analytical modeling, highlighting the characteristic pulse-like features in near-fault ground motions that distinguish them from far-field records.

The approximation of the velocity time-history in this study has been conducted based on the analytical closed-form models proposed by references [8] and [11]. Accordingly, the simulation of high-amplitude wavelets can be accomplished by employing Equation (1) and performing an analytical implementation of the FDP2 Pulse group of Equation (2). Additionally, for simulating the wavelets and spikes with distinctive extremum shapes, Equation (1) and the FDP1 Pulse in Equation (2) are applicable. Furthermore, since Equation (1) employs trigonometric statements, each simulated wavelet or pulse feature carries a specific frequency. On the other hand, the FDP1 Pulse in Equation (2) encompasses several frequencies that can be decomposed through the implementation of the Fourier Transform analysis. The utilization of Equation (1), proposed by Menun and Fu [8], generates a spectrum of pseudo-sinusoidal arrays corresponding to an assumed pulse period, as it combines trigonometric and exponential functions.

It's important to highlight that by conducting the aforementioned compositions and analyses concerning the designated time windows and the specified orientation axis, the resulting wave-like features with tuned increasing/decreasing configurations progressively attain heightened accuracy. Consequently, adjusting the designated orientation axis within the time window under investigation notably facilitates the attainment of the desired pulse or spike shape characterized by the actual record and its distinct peaks. The applicability of Equation (1) extends across a broader range within the time window under study, encompassing a variety of increasingly efficient wavelets with the assigned characteristics. As a result, the closed-form solution suggested in reference [11] is particularly suitable for representing long-period wavelets characterized by triangular shapes and sharp peaks. Conversely, utilizing the closed-form model proposed in reference [8] may reveal certain analytical inefficiencies when dealing with such wavelet shapes.

The BAM record exhibits a peak ground velocity of 121.48 cm/s, demonstrating pulse-like motion traits. Figure 2 illustrates a velocity time window spanning from second 2 to 4 for the TR component and its corresponding acceleration time-history. This window captures a substantial portion of the distinct coherent velocity pulse's energy. Notably, Figure 2 depicts a pulse-like velocity composition with an absolute maximum exceeding 50 cm/s in the negative domain, persisting from approximately second 2 to just past second 3 across the entire 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 Equation (1). The corresponding acceleration time-history of each approximation is also depicted alongside the velocity time-history, and shows the resultant computed acceleration. Additionally, the key specifications and parameters utilized for generating each simulation in the velocity time-history, along with their corresponding acceleration values, are delineated within each segmented time domain.



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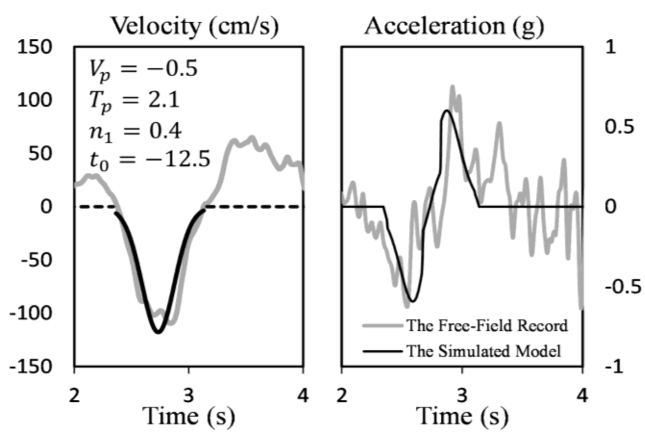
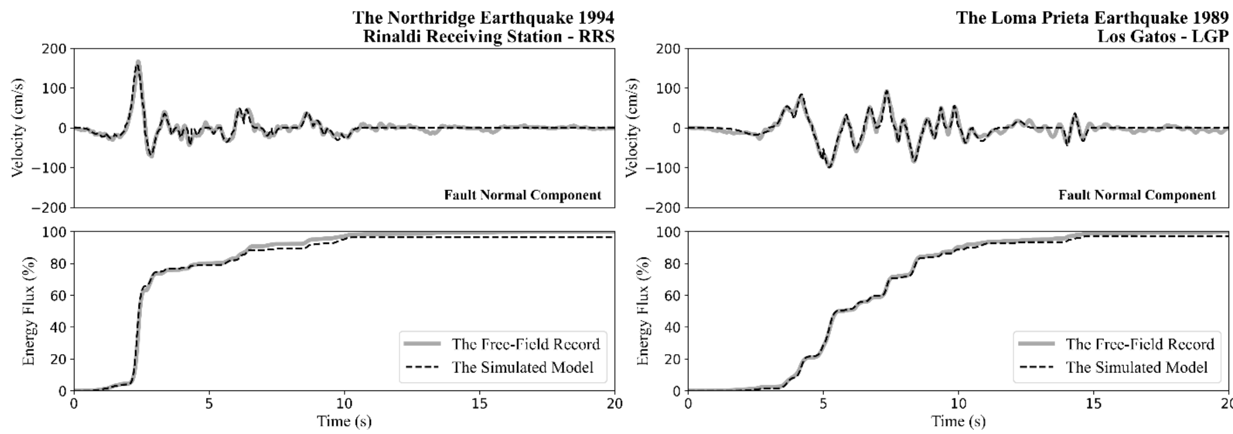


(b)

Fig. 2. Comparison of analytical pulse-like velocity simulation approaches demonstrated on the fault-normal component of the 2003 Bam earthquake (2-4 second window): (a) Two-step velocity pulse simulation with time domain subdivision, successfully capturing high-amplitude acceleration spikes (arrows). This approach demonstrates the importance of proper parameter selection in representing energy release characteristics; (b) One-step velocity pulse simulation without subdivision, showing inadequate representation of acceleration features despite matching overall velocity profile. This initial modeling step establishes the foundation for subsequent validation stages including energy coverage assessment, displacement analysis, and frequency content verification.

In Figure 2a, a two-step simulation of the velocity pulse-like composition is depicted. Despite both models sharing the same evaluated frequency, subdividing the analytical composition into two distinct pulse-type configurations could potentially impact modeling accuracy, particularly in terms of frequency content. Additionally, assessing this composition using two-step modeling leads to the simulation of energetic high-amplitude spikes in the ground acceleration time-history, as highlighted by the arrows. On the other hand, Figure 2b displays the same velocity pulse, which has been modeled in one analytical step without subdivision notes, failing 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 it is needed to extend the subject further to include a range of high-amplitude spikes. This approach is important for predicting the amount of kinetic energy released during intense ground motions. The primary goal of approximating the velocity time-history serves a dual purpose. Firstly, it aims to depict and fine-tune the selected closed-form wavelets precisely. Secondly, it seeks to appropriately assess the variation rates associated with the kinetic energy release diagram attributed to a strong earthquake record.

It should be noted that in the assessment and synchronizing of the kinetic energy released due to the closed-form modeling of the directivity process, two crucial subjects must be considered. These mentioned subjects are generally entitled as "convergence variation of the energy being released from the earthquake record" and "obtaining the resemblance to the rate of energy release by the earthquake record". In this respect, Figures 3 and 4 show the results of modeling and fitting the velocity and acceleration time-histories related to the TR component of the selected ground motions. Notably, in this modeling process, the parametric framework proposed by Menun and Fu [8] carries significant analytical weight and contributes extensively to the representation of the velocity time-histories. It is essential to underscore the significance of extending this modeling and simulation approach not only to TR but also to LN components, as each contributes uniquely to the structural seismic response. In this regard, Figures 5 and 6 provide complementary insights, focusing on the LN component. Incorporating the LN component enriches the analysis, offering a comprehensive understanding of the seismic characteristics of earthquake records. Thus, examining both TR and LN components enhances the representation of near-fault records, ultimately increasing the accuracy of subsequent structural analyses. Below each velocity time-history, a comparison has been made between the cumulative release of seismic energy associated with an earthquake record and that of the simulated model (Figures 3 and 5). This comparison ensures that the analytical closed-form modeling adequately captures at least 95% of the cumulative kinetic energy released by the respective free-field earthquake record.



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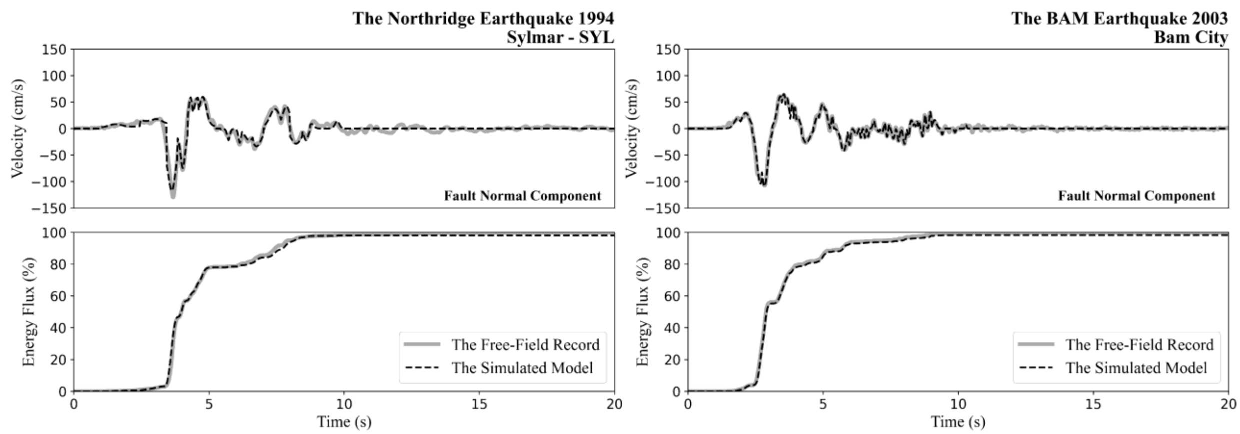

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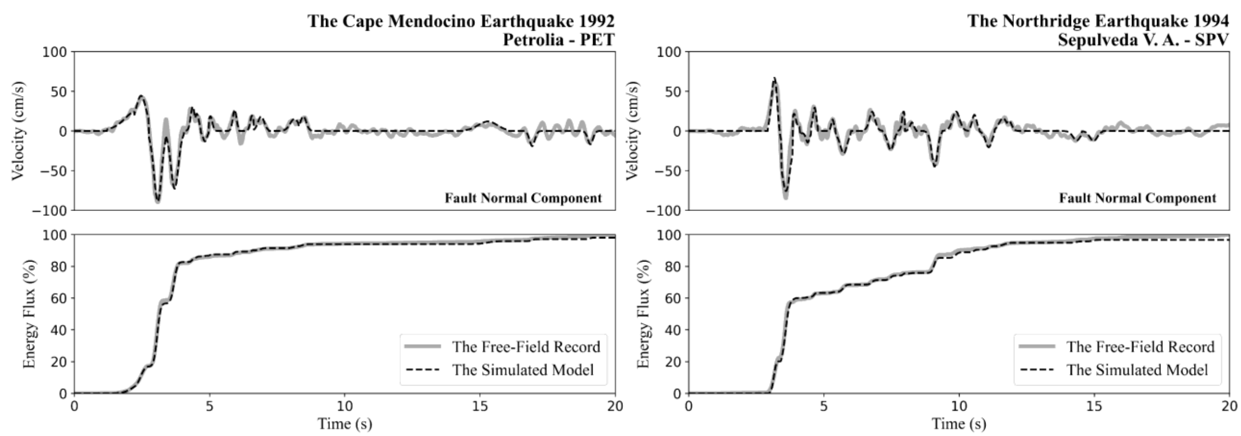
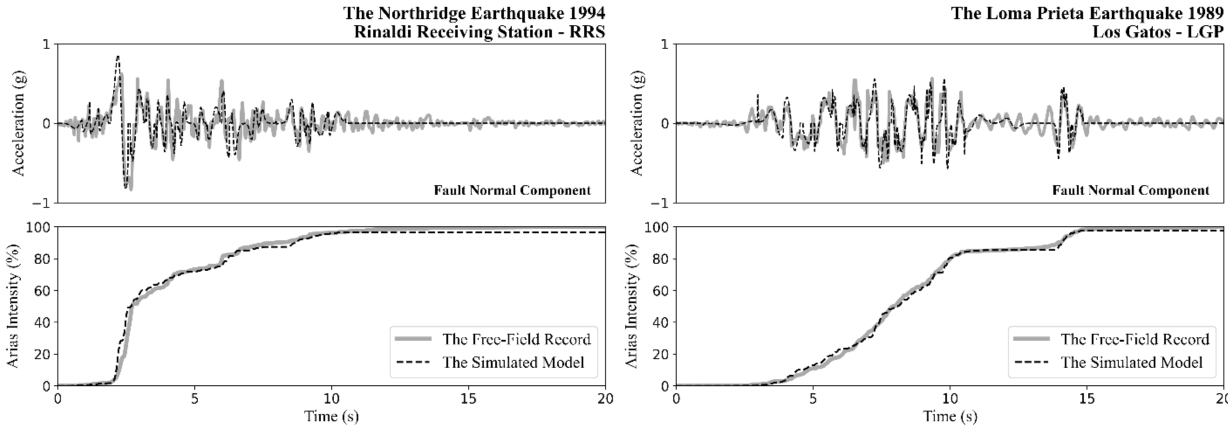


(c)

Fig. 3. Assigned closed-form modeling and fitted velocity time-histories related to the TR component as well as cumulative variation of corresponding released kinetic energy for the selected earthquake records: (a) the RRS 1994 and LGP 1989 records; (b) the SYL 1994 and BAM 2003 records; (c) the PET 1992 and SPV 1994 records.



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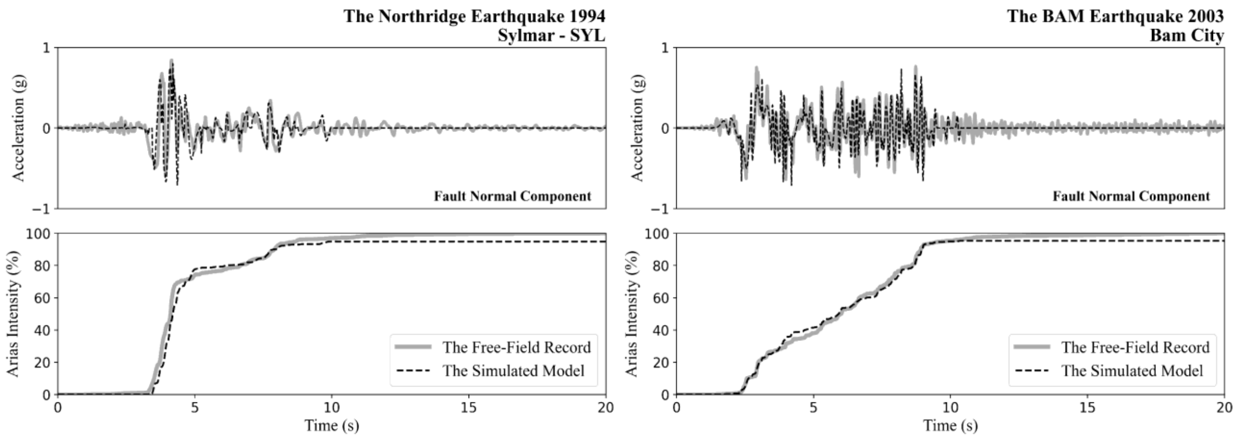

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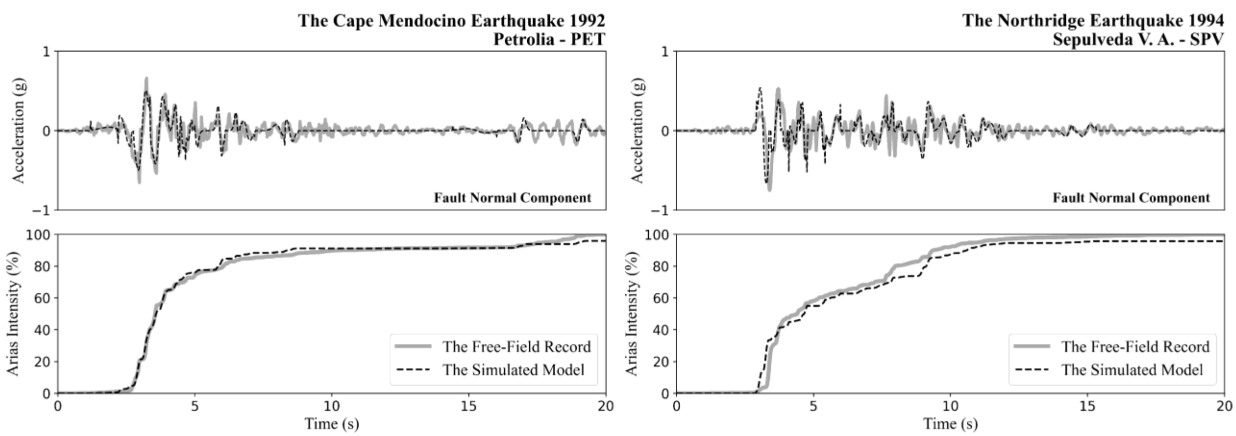


(c)

Fig. 4. Comparison of the acceleration time-histories related to the TR component of free-field earthquake records and closed-form simulated models as well as the corresponding Arias intensities: (a) the RRS 1994 and LGP 1989 records; (b) the SYL 1994 and BAM 2003 records; (c) the PET 1992 and SPV 1994 records.

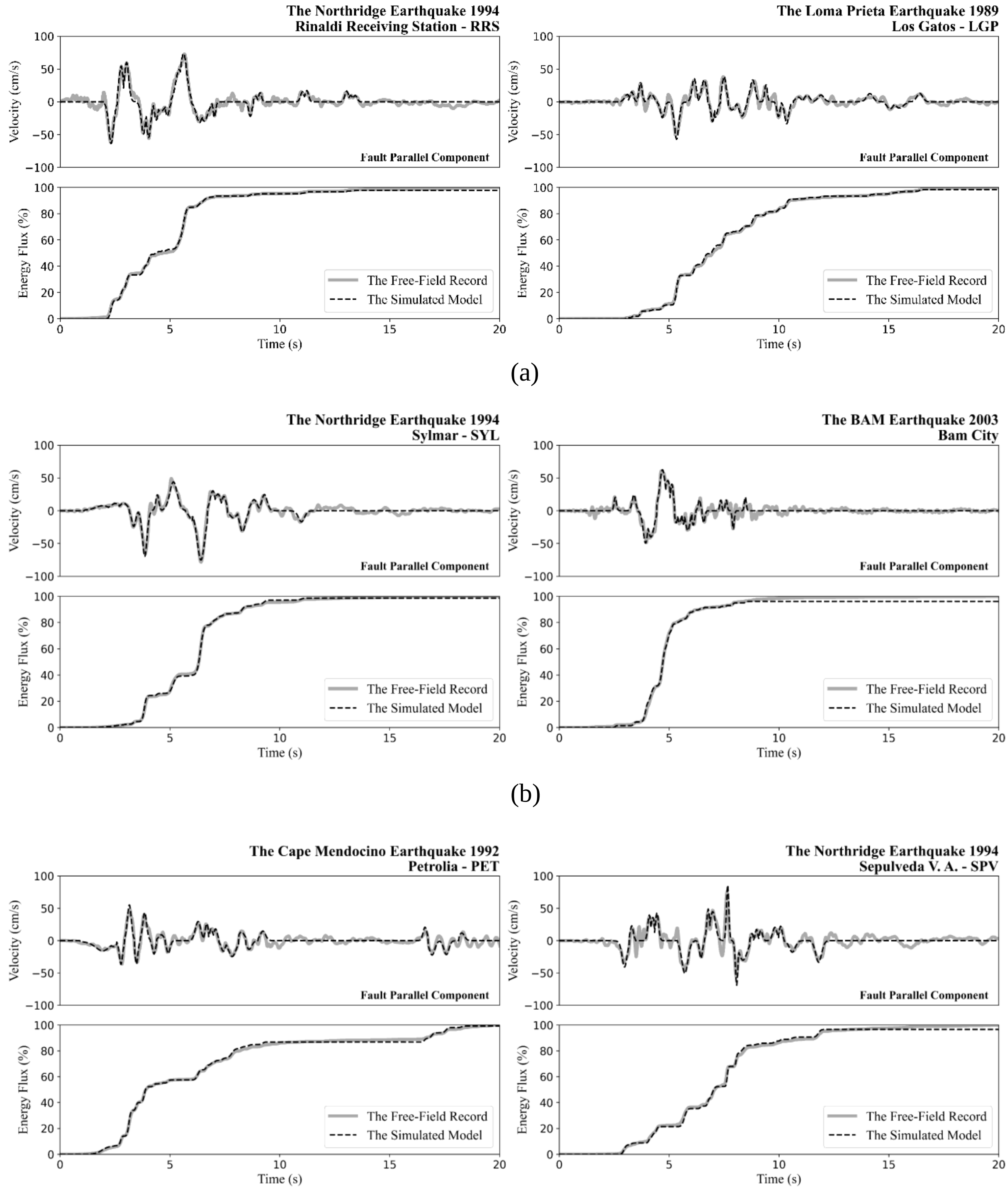
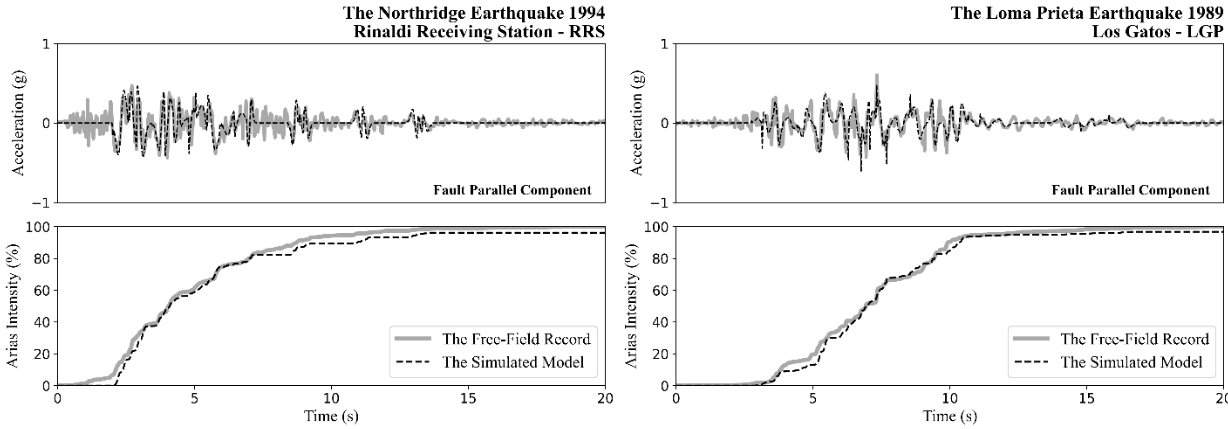


Fig. 5. Assigned closed-form modeling and fitted velocity time-histories related to the LN component as well as cumulative variation of corresponding released kinetic energy for the selected earthquake records: (a) the RRS 1994 and LGP 1989 records; (b) the SYL 1994 and BAM 2003 records; (c) the PET 1992 and SPV 1994 records.



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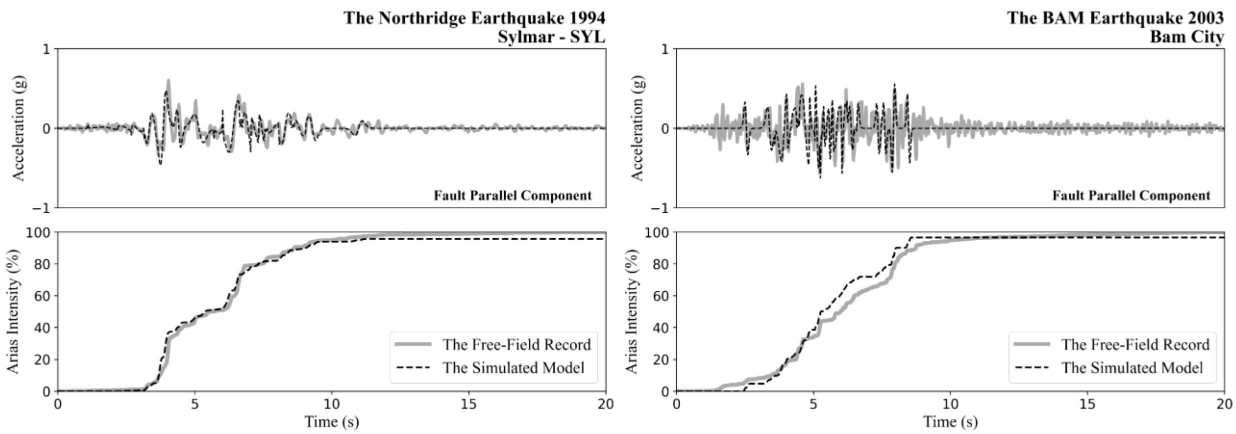

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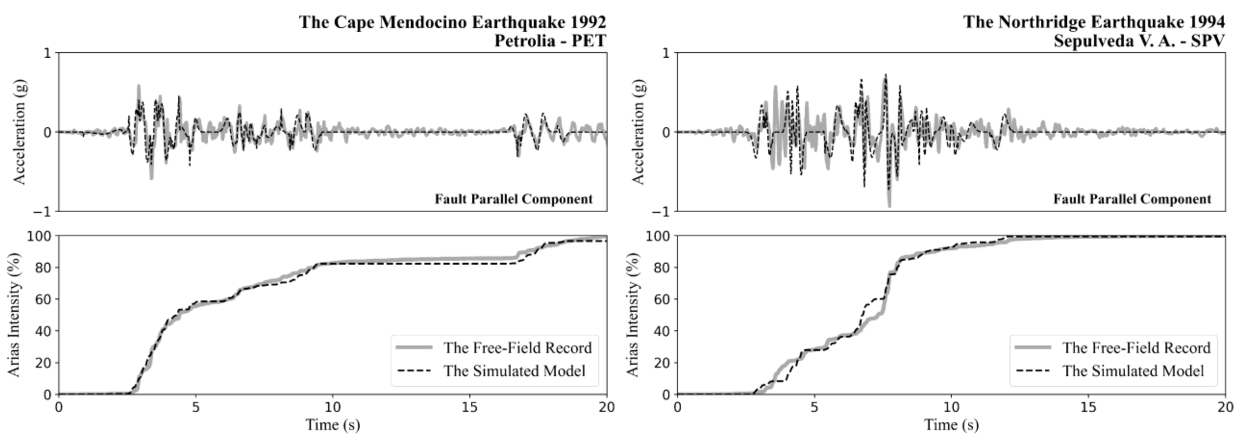

(c)

Fig. 6. Comparison of the acceleration time-histories related to the LN component of free-field earthquake records and closed-form simulated models as well as the corresponding Arias intensities: (a) the RRS 1994 and LGP 1989 records; (b) the SYL 1994 and BAM 2003 records; (c) the PET 1992 and SPV 1994 records.

Throughout the parameter selection and adjustment process for the assigned closed-form models, a meticulous approach was employed. This approach aimed to approximate the considered wavelets accurately and encompass a wider 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 windows under study. Furthermore, the implementation of the approved closed-form functions that satisfy mathematical differentiability and monotonicity conditions is essential. This is a specialized analytical domain, particularly relevant in modeling pulse-type ground motions characterized by multiple high-amplitude wavelets.

A crucial aspect of precision monitoring and verifying the prepared closed-form artificial ground motions entailed comparing the obtained acceleration time-history with that corresponding to free-field earthquake records. For this purpose, numerical differentiation was performed to obtain the acceleration time-history from the closed-form ground velocity function. Moreover, the Arias intensity, as a well-established power measure quantifying the intensity of ground shaking, was assessed for the analytical comparisons. The comparison between the TR and LN components of free-field recorded ground accelerations and their simulated closed-form modeling is depicted, with corresponding Arias intensities aligned beneath the time-histories (Figures 4 and 6). The analytical process involved utilizing closed-form statements and adopting computational facilitations to ensure that the parametric mathematical model approximates the free-field earthquake record. This is numerically prepared to ensure that the corresponding Arias intensity encompasses at least 95% of the companion parameters associated with the considered free-field earthquake record, mirroring the rate of change observed in the Arias intensity related to the original motion. Achieving this level of convergence, however, poses a challenge. As the analytical convergence of Arias intensity increases, it affects energy flux, prompting consideration of the user's needs regarding energy and intensity measures. This nuanced balance underscores the necessity for careful consideration during modeling and analysis, ensuring alignment with specific research objectives.

The comparison of displacement time-histories between the selected near-fault pulse-like earthquake records and their corresponding simulated counterparts is of paramount importance in this study. Figure 7 focuses on the TR component, while the subsequent Figure 8 examines the LN component. These figures provide a comprehensive visual representation of the similarities and differences between the original earthquake records and the corresponding simulated waveforms. By scrutinizing the ground displacement time-histories, one can discern how well the simulated counterparts capture the seismological characteristics of the original earthquake records. This comparison provides insights into the fidelity of the corresponding simulated waveforms. Additionally, discrepancies between the actual and simulated displacement time-histories offer valuable clues for refining the simulation parameters and improving the overall accuracy of the simulated records. Ultimately, this comparison serves as a critical step in ensuring the reliability and applicability of the simulated near-fault pulse-like records for subsequent structural analyses and seismic assessments.

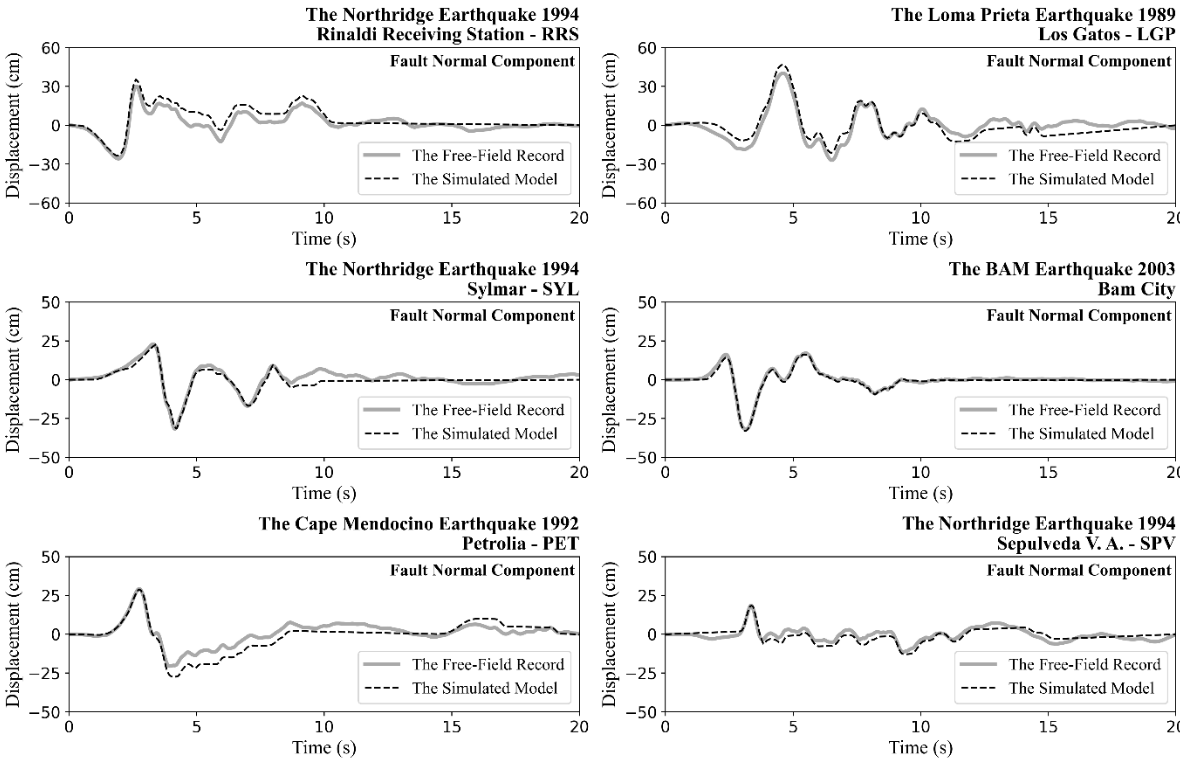

Fig. 7. Displacement time-history comparison for the TR component of the selected records and corresponding closed-form representations.

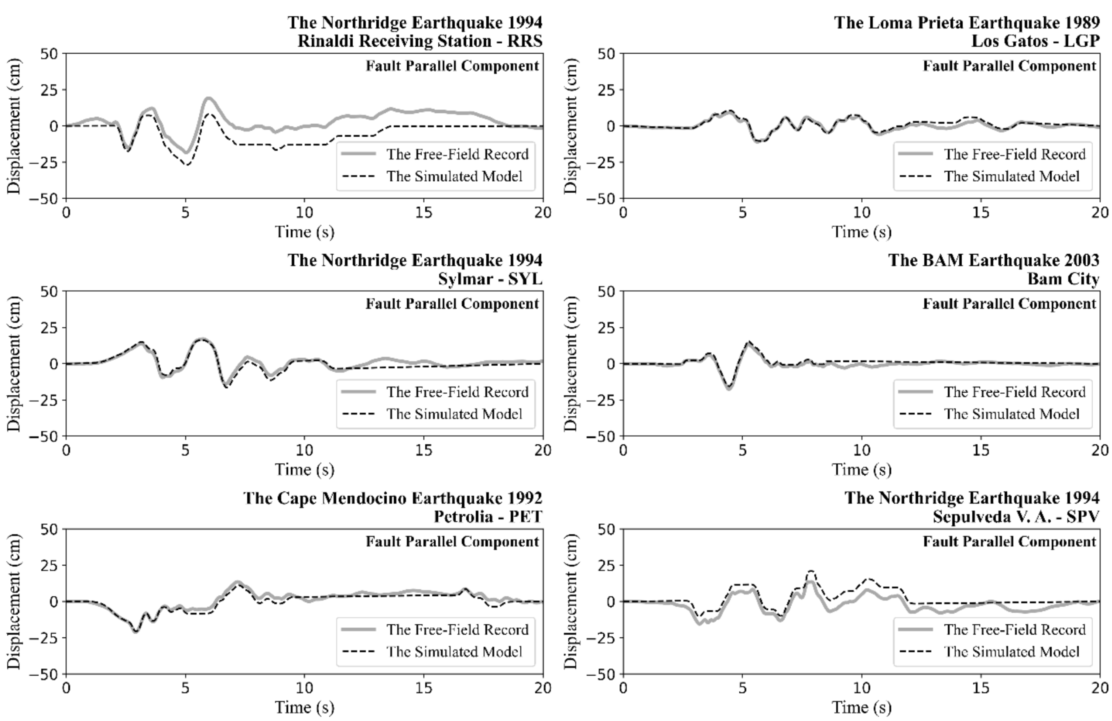

Fig. 8. Displacement time-history comparison for the LN component of the selected earthquake records and corresponding closed-from representations.

Additionally, to assess the numerical precision of the approximated frequency content and further validate the fidelity of the simulated counterparts, a Fourier spectrum analysis was performed. This analysis provides insights into the distribution of energy across different frequency components in both the original earthquake records and their simulated representations. Figures 9 and 10 illustrate the Fourier spectrum comparison due to the TR and LN components of the selected earthquake records and their companion closed-form artificial motions. The special intention behind this analysis is to approximate not only the amplitudes but also the temporal arguments of the assigned wavelets in the low to mid-range frequency domain, capturing the distinct pulse-like features as well as several companion energetic spikes. This comparison aids in gauging the efficacy of the modeling approach in accurately reproducing the frequency characteristics of the original seismic events.

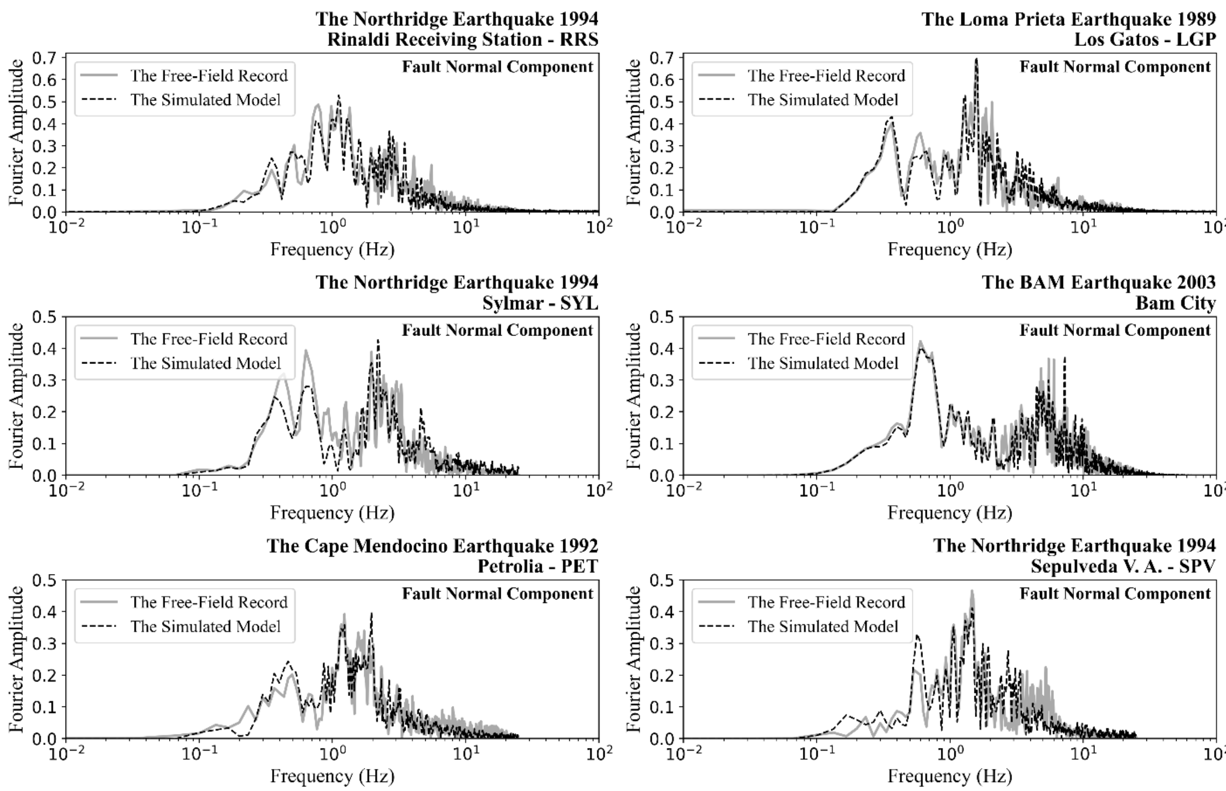

Fig. 9. Fourier spectrum comparison for the TR component of the selected earthquake records and corresponding closed-from representations.

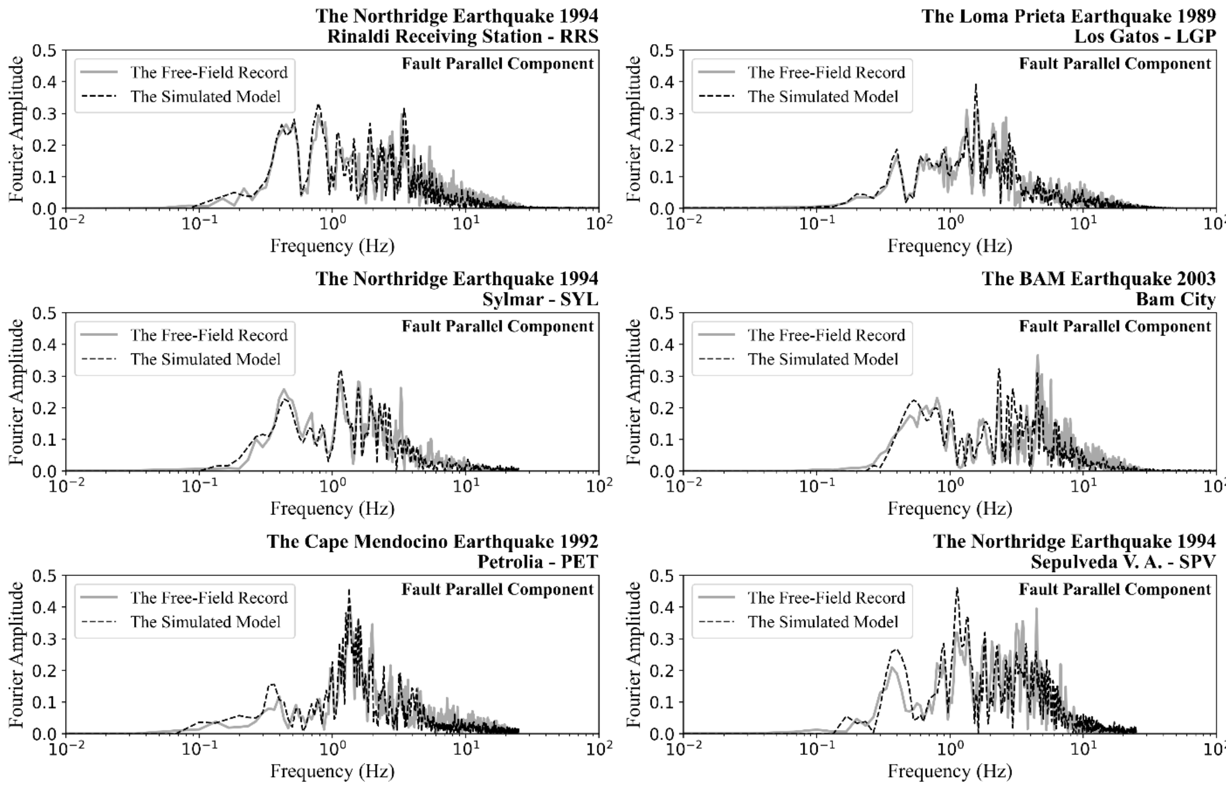

Fig. 10. Fourier spectrum comparison for the LN component of the selected earthquake records and corresponding closed-from representations.

Conclusion

The primary objective of this study was to investigate the numerical efficacy of two prominent mathematical closed-form models for approximating coherent velocity pulses displayed in the time-history of near-fault ground motions. To achieve this goal, simulation processes were conducted on six strong near-fault motions, comparing their performance against free-field earthquake records. Based on the assessment of the obtained results, it is indicated that by adopting suitable parametric statements and analytical techniques, relatively accurate approximations of near-field pulse-like motions can be achieved. Critical to this process is determining appropriate time windows for simulation and adjusting model parameters to encompass at least 95% of the cumulative kinetic energy released by the corresponding free-field record. Additionally, similar adjustments can enhance the accuracy of assigned intensity measures and improve the fidelity of closed-form simulations by aligning them with frequency content assessments.

Comparative analysis between the companion closed-form motions and free-field earthquake records reveals a favorable agreement, underscoring the potential effectiveness of the closed-form approach in accurately representing pulse-like ground motions. Furthermore, Fourier spectrum analysis provides further validation for the accuracy of the assigned closed-form method, indicating nearly precise representations of pulse-like earthquake records.

Additionally, the comparison of displacement time-histories between the simulated counterparts and the original earthquake records further validates the fidelity of the closed-form models in capturing the physical characteristics and directivity effects of near-fault ground motions. This comprehensive assessment provides confidence in the reliability and accuracy of this analytical approach for seismic analysis and earthquake engineering applications.

While these closed-form models demonstrate strong performance, the manual parameter selection process limits their scalability for large-scale applications. Future research should focus on developing automated parameter optimization techniques and exploring machine learning approaches to enhance computational efficiency across varying geological conditions.

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