



ANALYSIS ON RESPONSE OF DYNAMIC SYSTEMS TO PULSE SEQUENCES EXCITATION

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Near-fault ground motions with long-period pulses can place severe demands on structures near an active fault. These pulse-type ground motions can be represented by pulse sequences with simple shapes. Half-sinusoidal pulse sequences are used to approximate recorded ground motions and dynamic responses of SDOF system under the excitation of these pulse sequences are studied. Four cases are considered: (1) variation in duration of successor sub-pulse; (2) variation in duration of predecessor sub-pulse; (3) variation in amplitude of successor sub-pulse; and (4) variation in amplitude of predecessor sub-pulse. The corresponding acceleration, velocity and displacement response spectra of these pulse sequences are studied. The analysis on SDOF system shows that in some cases the responses are strongly affected by the changes of duration and/or amplitude of the sub-pulse. The study can be useful to understand the influences of sub-pulse in the near-fault pulse-type ground motions.

Keywords: near-fault, pulse sequences, sub-pulse, variations in duration and amplitude, response

1. Introduction

Ground motions in the vicinity of the fault are often characterized by distinct acceleration, velocity and displacement pulses, especially in the ground velocity. These ground motions can be approximated by some pulse sequences with simple shapes. If a simple pulse model can be used with a relative accurate representation to the pulse in recorded ground motions, the studies on the

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theories and applications will be facilitated because the controlling parameters of the pulses are easily determined and the expressions of the pulses can be in analytic forms. The simple pulse model, such as half- and full-cycle sinusoids, had been used long ago by Veletsos et al. (1965) to develop elastic and inelastic response spectra, and the full-cycle sinusoidal velocity pulse was used to approximate the Eureka ground motion recorded in the California earthquake of December 21, 1954. In a series of papers by Makris et al. (2000, 2003) and Spyarakos et al. (2008), three sinusoidal types of simple velocity pulses were employed, which can represent half-, full-, and multi-pulse in the ground velocity. The idealized simple pulse models were used by Sasani et al. (2000) to investigate normalized response spectra, concluding that the spectra for simple velocity pulses are not only a good representation of the spectra for recorded pulse-type ground motions, but also could be used as a useful tool in the design and retrofit of structures. Agrawal et al. (2002) presented an approach for modeling velocity pulse by using decaying sinusoidal pulses, the validity and usefulness of the proposed model was demonstrated using the pulse-type ground motions recorded in the Northridge earthquake of January 17, 1994 and Landers earthquake of June 28, 1992. Hall et al. (1995, 1998) and Alavi et al. (2000, 2004) investigated the responses of SDOF and MDOF system using triangle velocity pulses. Dai et al. (2004) studied the elastic response spectra of SDOF system under triangle acceleration pulses with variable amplitude of the sub-pulse. Zhang et al. (2005) discussed the characteristics of elastic spectra for half-, full- and three-half-cycle sinusoidal acceleration pulses, pointing that the acceleration pulse imposes much higher base shear demands on resonance-band structures than non-resonance-band structures. Xie et al. (2005) and Mylonakis et al. (2006) studied the elastic and inelastic responses for several simple pulse models with different shapes, which lead to an insight on how to select simple pulses for use in engineering, in particular when local site effects are considered in near-fault regions.

Three main reasons triggered the research we describe in this paper. First, the pulse in the ground velocity can control the responses of a structure compared with the entire ground motion despite its short duration. And the simple pulse sequences, which are used to represent the pulse in recorded ground motions, can also give a representation to the entire ground motion with an acceptable accuracy. One demonstration is showed in Figure 1, which is a pulse-type ground motion recorded from the Rinaldi Receiving Station (RRS, S33W component) in the 1994 Northridge earthquake. The duration of this pulse in the ground velocity lasts about 1.25s. The pulse is approximated by two half-sinusoidal pulses, and the corresponding pulse in the ground acceleration is derived from the two half-sinusoidal pulses in the ground velocity. It can be seen that there are many similarities in the response spectra among entire ground motion, the pulse in the ground velocity and the simple pulse sequences. Second, the amplitude and duration of the main-pulse and sub-pulse in the ground velocity are usually not equal, and this can be seen in Figure 1. Third, most of the current simple pulse models disregard variations in duration and

amplitude of sub-pulse in recorded ground motions. Though Dai et al. (2004) gave a preliminary study on the effects of variation in amplitude of sub-pulse on elastic spectra, they focused on the half- and full-cycle pulses in the ground acceleration, rather than in the ground velocity. Consequently, their results may be useful to near-fault pulse-type ground motions generated by the fling step effect, which are characterized by a large half-pulse in the ground velocity.

This paper deals with characteristics of response spectra and normalized response spectra when considering the variations in duration and amplitude of successor and predecessor sub-pulses. This study will lead to an understanding of the influences of sub-pulse in the near-fault pulse-type ground motions.

2. Representation of the Velocity Pulse

The pulse in the ground velocity can be either generated by forward rupture directivity or generated by fling step. Pulses from the two effects have different characteristics. Forward directivity is a dynamic phenomenon and produces a full-cycle velocity pulse, whereas fling step produces a half-cycle velocity pulse. These two types of pulses all can be represented by the pulse sequences. A general form of the pulse sequence is showed in Figure 2. The pulse sequence is defined by two half-cycle pulses, the period of each half-cycle pulses (T_1 , T_2), and their corresponding amplitudes (V_1 , V_2). The pulse sequence covers all the possible forms of a velocity pulse. Mathematically this is expressed as

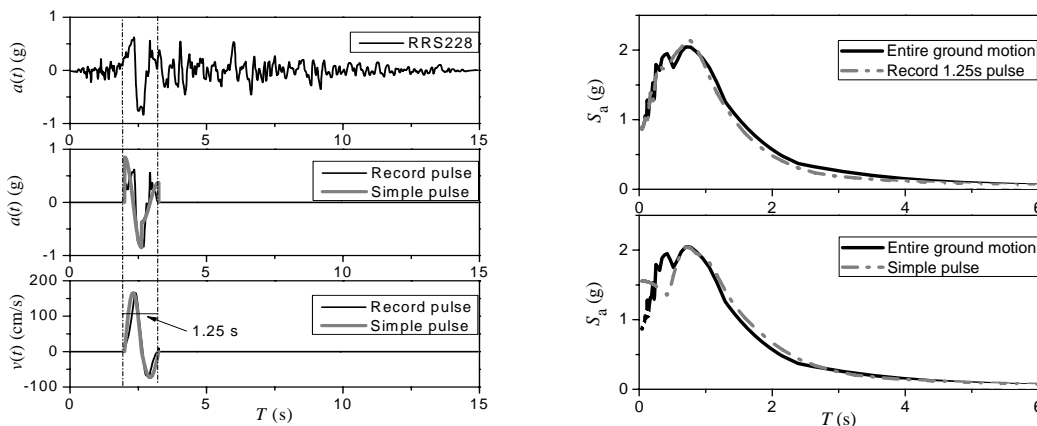


Figure 1. The entire ground motion, pulse, simple pulse, and response spectra

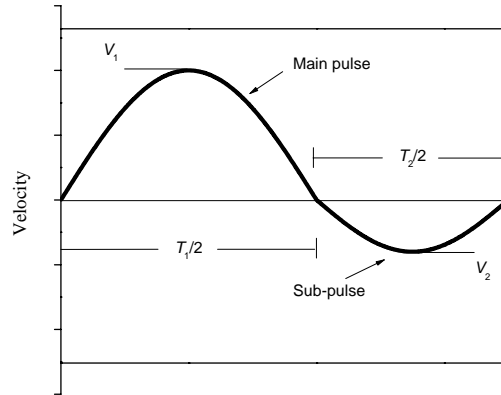


Figure 2. General form of a velocity pulse

$$v_g(t; V_1, V_2, T_1, T_2) = \begin{cases} V_1 \sin\left(\frac{2\pi}{T_1}t\right) H\left(\frac{T_1}{2}-t\right) - V_2 \sin\frac{2\pi}{T_2}\left(t-\frac{T_1}{2}\right) H\left(t-\frac{T_1}{2}\right) & 0 < t \leq (T_1 + T_2)/2 \\ 0 & \text{otherwise} \end{cases} \quad (1)$$

where $H(\cdot)$ is the Heaviside function. Consider an elastic SDOF system under such excitation

$$\ddot{X} + \omega_n^2 X = -\dot{v}_g(t; V_1, V_2, T_1, T_2) \quad (2)$$

The relative displacement response is given in the following form (three segments for briefly: $0 < t \leq T_1/2$, $T_1/2 < t \leq (T_1 + T_2)/2$, $t > (T_1 + T_2)/2$).

If $\theta_1 \neq \omega_n, \theta_2 \neq \omega_n$

$$X = \begin{cases} \frac{V_1 \theta_1}{\theta_1^2 - \omega_n^2} \cdot (A_1 + A_2) \\ \frac{V_1 \theta_1}{\theta_1^2 - \omega_n^2} \cdot (A_3 + A_4) + \frac{V_2 \theta_2}{\theta_2^2 - \omega_n^2} \cdot (A_5 + A_6) \\ \frac{V_1 \theta_1}{\theta_1^2 - \omega_n^2} \cdot (A_7 + A_8) + \frac{V_2 \theta_2}{\theta_2^2 - \omega_n^2} \cdot (A_9 + A_{10}) \end{cases} \quad (3a)$$

If $\theta_1 = \omega_n, \theta_2 \neq \omega_n$

$$X = \begin{cases} -\frac{V_1 t}{2\omega_n} \cdot A_1 \\ \frac{V_2 \theta_2}{\theta_2^2 - \omega_n^2} \cdot (A_1 + A_6) - \frac{V_1 \pi}{2\omega_n^2} \cdot A_1 \\ \frac{V_2 \theta_2}{\theta_2^2 - \omega_n^2} \cdot (A_1 + A_{11}) - \frac{V_1 \pi}{2\omega_n^2} \cdot A_1 \end{cases} \quad (3b)$$

If $\theta_1 \neq \omega_n, \theta_2 = \omega_n$

$$X = \begin{cases} \frac{V_1 \theta_1}{\theta_1^2 - \omega_n^2} \cdot (A_1 + A_2) \\ \frac{V_1 \theta_1}{\theta_1^2 - \omega_n^2} \cdot (A_3 + A_4) + \frac{V_2 (t - \pi/\theta_1)}{2\omega_n} \cdot A_4 \\ \frac{V_1 \theta_1}{\theta_1^2 - \omega_n^2} \cdot (A_7 + A_8) + \frac{V_2 \pi}{2\omega_n^2} \cdot A_4 \end{cases} \quad (3c)$$

If $\theta_1 = \omega_n, \theta_2 = \omega_n$

$$X = \begin{cases} -\frac{V_1 t}{2\omega_n} \cdot A_1 \\ \frac{\pi V_1 + (-\pi + \omega_n t) V_2}{2\omega_n^2} \cdot A_1 \\ -\frac{\pi (V_1 + V_2)}{2\omega_n^2} \cdot A_1 \end{cases} \quad (3d)$$

where $\theta_1 = 2\pi/T_1$ and $\theta_2 = 2\pi/T_2$; ω_n is the natural circular frequency of vibration; t is the time variable. And

$$\begin{aligned}
 A_1 &= -\cos \omega_n t & A_2 &= \cos \theta_1 t \\
 A_4 &= -\cos[\omega_n(t - \pi/\theta_1)] & A_6 &= -\cos[\theta_2(t - \pi/\theta_1)] \\
 A_{10} &= \cos[\omega_n(t - \pi/\theta_1 - \pi/\theta_2)] & A_{11} &= -\cos[\omega_n(t - \pi/\theta_2)] \\
 A_3 &= A_7 = A_1, \quad A_8 = A_4, \quad A_9 = A_5 = -A_4
 \end{aligned}
 \tag{4}$$

Though fling step can generate pulse, the severest damaging characteristics of this type of ground motions are mainly attributed to the large ground displacement, rather than the velocity pulse. However, the damage potentials of ground motions influenced by forward directivity are directly related with the velocity pulse. As a result, we will pay more attention to the directivity pulse. Four cases are studied in the following context: variation in duration of successor sub-pulse, variation in duration of predecessor sub-pulse, variation in amplitude of successor sub-pulse, and variation in amplitude of predecessor sub-pulse. For simplicity, T_1 and T_2 are fixed and set with the same value when taking account to variation in amplitude, and V_1 and V_2 are fixed in the same way when taking account to variation in duration. Figure 3 shows the details of the four cases, in which the V_{max} and V_m are maximum velocity and velocity of main-pulse, respectively. The unit in the figure is second for duration and cm/s for velocity.

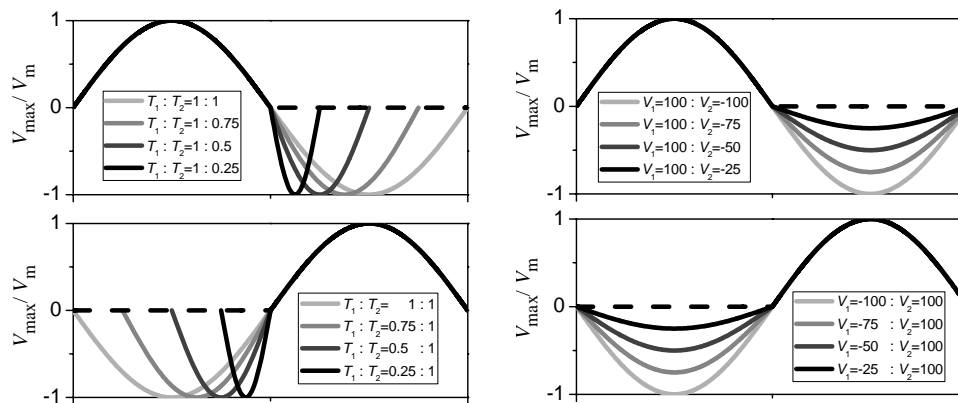


Figure 3. Four cases: variation in duration of sub-pulse with fixed V_1 and V_2 and variation in amplitude of sub-pulse with fixed T_1 and T_2

The peak values of pulse sequences which represented by Equation (1) can be computed by expression (5). The ratios of peak values caused by variations in duration and amplitude are listed in Table 1. For the case of variation in duration, it can be seen that if the duration of velocity sub-pulse reduces, the peak acceleration will increase, while the peak displacement will keep constant. For other cases, the variations have no influences on the peak value of ground motion. These characteristics are useful for discussing normalized response spectra.

$$\begin{cases} a_{g,Max} \\ v_{g,Max} \\ x_{g,Max} \end{cases} = \begin{cases} \text{Max} \{ 2\pi/T_1 \cdot V_1, & 2\pi/T_2 \cdot V_2 \} \\ \text{Max} \{ V_1, & V_2 \} \\ \text{Max} \{ T_1 \cdot V_1/2\pi, & T_2 \cdot V_2/2\pi \} \end{cases} \quad (5)$$

Table 1. Influence of sub-pulse on the peak value of ground motion

	variation in duration		variation in amplitude	
	successor 1 (s)	predecessor 1 (s)	successor 100 (cm)	predecessor 100 (cm)
Main pulse				
Ratio of sub-pulse	1:0.75:0.50:0.25 (s)	1:0.75:0.50:0.25 (s)	100:75:50:25 (cm)	100:75:50:25 (cm)
Ratio of peak acc.	1:1.33:2:4	1:1.33:2:4	1:1:1:1	1:1:1:1
Ratio of peak dis.	1:1:1:1	1:1:1:1	1:1:1:1	1:1:1:1

3. Natural Responses

Some basic characteristics can be drawn from the acceleration, velocity and displacement response spectra shown in Figure 4 and 5. In general, the response spectra can be approximately divided into three segments: Segment I, $0 < T/T_m < 0.6$, Segment II, $0.6 < T/T_m < 3$, and Segment III, $T/T_m > 3$. Where T is the period of structure, T_m is the duration of main-pulse. It is crudely regarded that Segment II is the resonance band, while Segment I and Segment III are non-resonance bands.

3.1. Variation of Sub-Pulse Duration

Acceleration response spectra exhibit the following features: For successor sub-pulses with shorter duration, they produce larger spectral accelerations in Segment I. The largest response belongs to the case $T_1:T_2=1:0.25$, and the smallest one belongs to the case $T_1:T_2=1:1$. The large acceleration will result in large base shear. It is may be concluded that the acceleration responses in Segment I are controlled by the sub-pulse in ground velocity, and the responses are at least no less than the full-cycle pulse sequence with equal duration and amplitude between the main-pulse and sub-pulse (hereafter simplified as full pulse sequence). It should be noted that the equal amplitude in this paper means that the two amplitudes have same absolute values; however, they can have opposite signs. At most periods in Segment II, decays of the sub-pulse make smaller

acceleration responses. For a structure whose period falls in Segment III, the influences of sub-pulse duration seem negligible. The decays of sub-pulse cause the peak acceleration response to shift to shorter periods. The influences of predecessor sub-pulse have the similar characteristics with the successor sub-pulse. In a word, the duration of sub-pulse in a ground velocity can change the structural acceleration response dramatically, and the peak acceleration response may not occur in the resonance band.

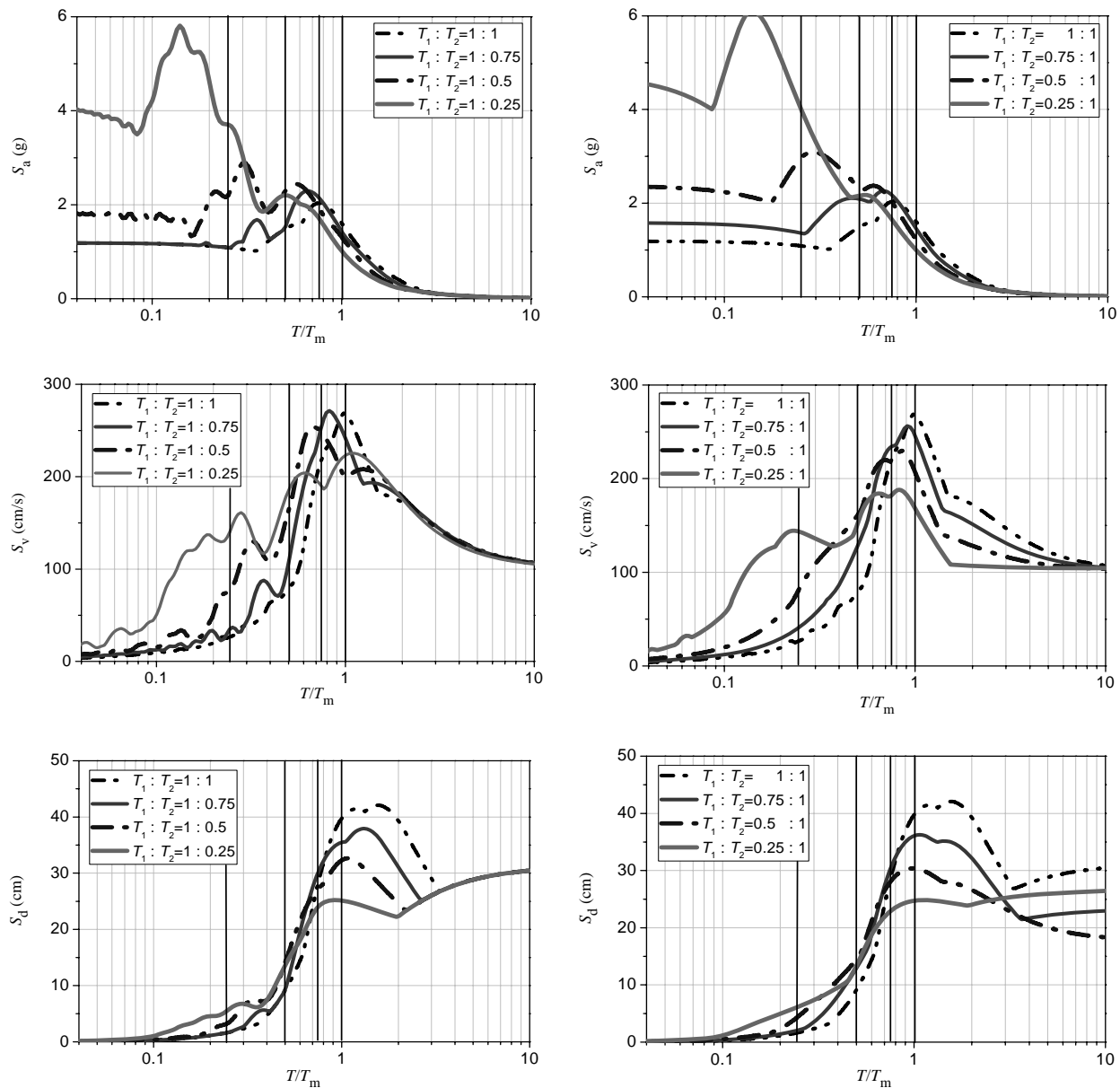


Figure 4. Acceleration, velocity, and displacement response spectra (amplitudes fixed, sub-pulse durations changing)

Velocity response spectra exhibit the following features: Successor sub-pulses with shorter duration change the spectral velocities in Segment I and Segment II, like acceleration response, the larger spectral values are found in Segment I for the shorter duration sub-pulses. The largest response belongs to the case $T_1:T_2=1:0.25$, and the smallest one belongs to the case $T_1:T_2=1:1$. The influences of sub-pulse duration are very small in Segment III. For predecessor sub-pulse, the velocity spectra show similar behaviors in Segment I comparing with the successor sub-pulse. However, quite different behaviors are shown at the periods in Segment II and Segment III, where the influences are still large. At most periods in Segment II and Segment III, decays of the sub-pulse make smaller velocity responses. The influences are negligible only when the structural period far exceed the main pulse period. Some conclusions can be given: the velocity responses in Segment I are controlled by the sub-pulse in the ground velocity, and the responses are at least no less than the full pulse sequence. At most periods in Segment II and Segment III, the velocity responses are controlled by the full pulse sequence.

The following characteristics are made for displacement response spectra: Comparing with acceleration and velocity response spectra, the influences of successor pulse are smaller in Segment I. This indicates that the displacement response is less sensitive to the variation of sub-pulse in the ground velocity when the structural periods fall into this segment. The spectral displacements at most periods in this segment are a little larger for the pulse sequence with shorter duration sub-pulse. Large influences are found in Segment II. In this segment, spectral displacements decay when the sub-pulse durations decrease. It seems no influences in Segment III since sub-pulses with different duration give the same spectral displacement. For predecessor sub-pulse, the similar characteristics are exhibited with the successor sub-pulse. However, there are some differences in Segment III, where the influences are large and discrete. The peak spectral displacement occurs when the structural period far exceeds main-pulse duration for the case $T_1:T_2=1:0.25$, rather than in the resonance bond. For predecessor sub-pulse, this phenomenon can also be detected when the sub-pulse duration is short enough. The displacement responses in Segment I are controlled by the sub-pulse in the ground velocity, and in Segment II and III are controlled by the full pulse sequence.

3.2. Variation of Sub-Pulse Amplitude

Acceleration response spectra exhibit the following features: It seems that there are no influences on acceleration responses in Segment I and Segment III by variation in amplitude of the successor sub-pulse. In the whole periods, the sub-pulse with largest amplitude ($V_1:V_2=100:-100$) controls the acceleration responses. For predecessor sub-pulse, the influences exist in Segment I and Segment II, the sub-pulse with large amplitude ($V_1:V_2=-100:100$) controls the acceleration

responses in the whole periods. The influences in Segment III are very small. Unlike the case for successor sub-pulse, the influences are large in Segment I.

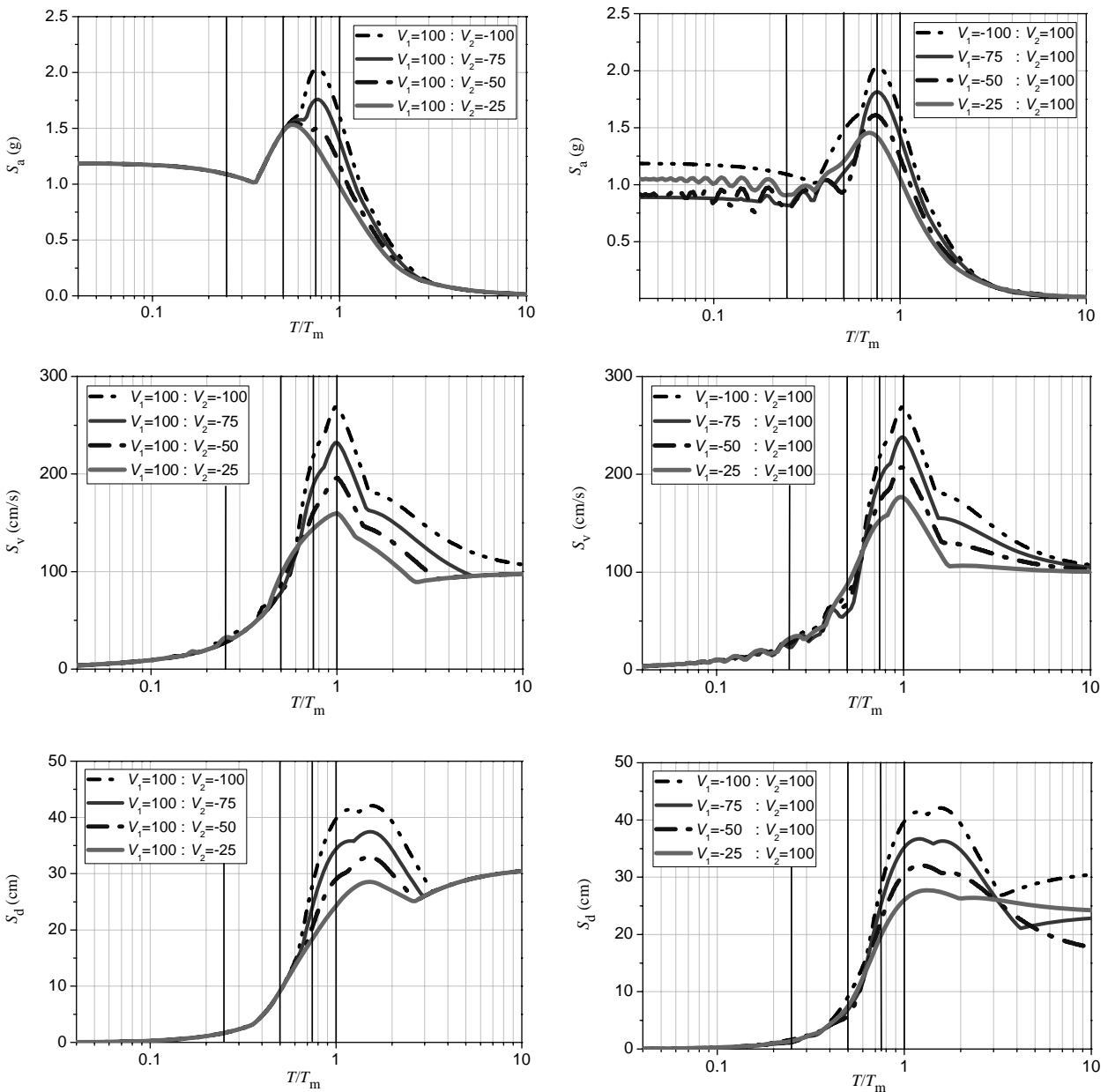


Figure 5. Acceleration, velocity, and displacement response spectra (durations fixed, sub-pulse amplitudes changing)

Velocity response spectra exhibit the following features: Successor sub-pulses with larger amplitude produce larger spectral velocities in Segment II and III. However, produce similar spectral velocities in Segment I. The sub-pulse with largest amplitude ($V_1:V_2=100:-100$) controls

the velocity responses in the whole periods. In very long periods, the influences seems becoming small again. The predecessor sub-pulse exhibits similar influences with the successor sub-pulse. Peak spectral velocities seem appear at the same period.

The following characteristics are made for displacement spectra: The influences of successor sub-pulses only exist in the resonance bond Segment II. In this segment, the sub-pulses with larger amplitudes produce larger spectral displacements. For predecessor sub-pulse, similar characteristics are found in the resonance bond Segment II. The influences in Segment I are small. However, the influences in Segment III are large. The peak spectral displacement occurs when the structural period far exceeds main-pulse duration for the case $V_1:V_2=100:-25$, rather than in the resonance bond. For predecessor sub-pulse, this phenomenon can also be detected when the sub-pulse amplitude is small enough. For both successor sub-pulse and predecessor sub-pulse, the full pulse sequence controls the responses in the whole periods.

4. Normalized Responses

The variation in duration of velocity sub-pulse changes the peaks of ground acceleration. In this section, we particularly discuss the characteristics of normalized acceleration response spectra for the case of variation in duration. For other cases, the normalized response spectra have the same shapes with their corresponding response spectra. The results are plotted in Figure 6.

Normalized acceleration response spectra exhibit the following features (variation in duration): For the case of successor sub-pulse, it shows that the maximum acceleration amplification effect may be caused by the ground motion with shorter sub-pulse duration. In Segment II, the amplification effect reduces as the durations of sub-pulse decrease. The influences of variation in sub-pulse duration are small in Segment III. The predecessor sub-pulse exhibits the similar characteristics with the case of successor sub-pulse. In general, either for successor sub-pulse or predecessor sub-pulse, the decay of sub-pulse duration causes the maximum acceleration amplification effect to shift to shorter periods. The maximum amplification effect in Segment I may belong to pulse sequence with shorter sub-pulse duration, and the full pulse sequence controls the responses in Segment II and Segment III.

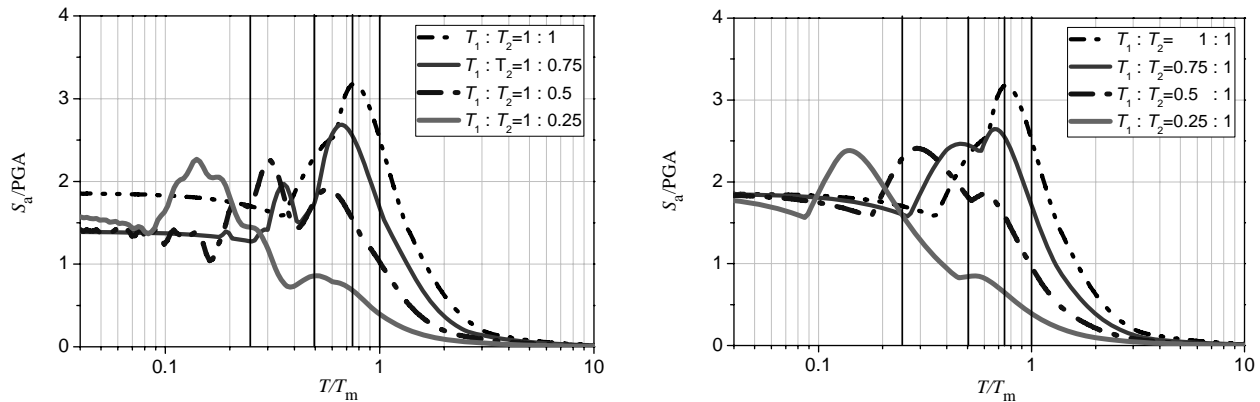


Figure 6. Normalized acceleration response spectra for the case of variation in duration

5. Conclusion and Discussion

Fundamental dynamic characteristics of velocity pulse sequences which resemble the near-fault ground motions are studied by using simplified combinational sinusoidal main-pulse and sub-pulse. The following conclusions can be drawn:

The spectral acceleration response in short periods is largely dependent with the duration of sub-pulse in the ground velocity. The velocity response and displacement response in short periods are also dependent with the duration of sub-pulse; however, the influences of sub-pulse have a reducing trend comparing with the influences on the spectral acceleration response. The peak spectral displacement response may occur not in the resonance bond, but occurs when the structural period far exceeds main-pulse duration for the case of a main-pulse with a short enough duration sub-pulse. The maximum acceleration amplification effect in short periods may be caused by the sub-pulse with short duration. The decay of sub-pulse duration causes the periods corresponding to peak acceleration response and maximum acceleration amplification effect to shift to shorter periods.

As shown in this study, the responses of structure are directly related with the main-pulse, sub-pulse, and their relations. This triggers us to reconsider the capacity of approximation by a simple wave with equal main-pulse and sub-pulse duration and amplitude. Perhaps a pulse sequence is a better choice.

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