Response to simple pulses representing near-fault ground motions

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Abstract

Near-Fault earthquake ground motions have been observed in previous researches to have strikingly different response characteristics as compared to far-field earthquakes. Use of conventional measures to quantify the earthquake characteristics of such ground motions for use in structural design is therefore inappropriate. An understanding of the peculiar characteristics of such ground motions is established by scrutinizing the structural response to simple representative pulse motions consisting of single-cycle sinusoidal pulses. Elastic and inelastic response of a SDOF system and elastic response of an seimic isolated system are evaluated and the pulse period where the response peaks is found to depend on the response quantity being considered and the level of target ductility required in the case of inelastic response. Structural response to pulse motions is observed to peak away from the expected resonating system that has the same natural period as the period of the input pulse motion due to impulsive nature of the input motion that is incapable of establishing a resonating response. Based on the observations of this study, it is established that appropriate cosiderations should be made for the pulse period of earthquake for design in near-fault zones.

1 Introduction

Earthquake ground motions recorded in the vicinity of the fault are found to have significant energy content in the long period range. Velocity time-history of such records is characterized by a distinct low frequency velocity pulse. Response evaluation of such ground motions has been found to impose significantly different structural demands than expected from the conventional code based design (Mehrdad Sasani and Vitelmo V. Bertero 2000.)

It is therefore imperative to take into account this difference for the design of structures located in near-fault zones. Identification of suitable input ground motion time histories in the case of response history analysis or the design spectrum for code defined response spectrum based design becomes crucial in such cases. Recent research on the response to near-fault earthquakes has shown significant dependence of structural response on pulse period of the near-fault ground motions (Attalla, Paret, and Freeman 1998.) This implies that the conventional record selection procedures based on ground motion prediction equations and hazard curves might be insufficient with regards to near-fault earthquakes. An appropriate structure specific identification scheme for near-fault ground motions is therefore necessary.

In order to comprehensibly understand the characteristics of structural response to near-fault ground motions, a detailed study with simple structural models and representative velocity pulses is undertaken in this study. A number of previous researches on near-fault ground motion response have found simple velocity pulses to adequately approximate the response characteristics for the period range in the vicinity of the dominant pulse period of near-fault earthquake ground motions (Alavi and Krawinkler 2004.) This simplification in this study is therefore not unwarranted. Furthermore, study with simple representative pulses allows a clearer understanding of the response characteristics that may be missed when analyzing with more complex ground motions or structural systems.

2 Representative pulse motions

Near-fault ground motions generated as a result of the directivity of propagating fault posses most of the energy released during faulting in the form of a long period pulse. Zhai et al. (2013) found upwards of 30% of the ground motion energy to be contained in the velocity pulses of respective near-fault ground motions. And since the structural damage suffered during an earthquake is directly related to the input energy of the ground motion, the representative velocity pulses offer an appropriate representation for evaluation of response to near-fault earthquakes.

A number of simplified pulse models have been used in the past researches to simulate near-fault earthquake response. Simple pulses of various shapes including sinusoidal (Makris and Chang 2000; Mollaioli et al. 2006,) triangular (Alavi and Krawinkler 2004,) and rectangular (Sasani 2006) pulses have been used to approximate actual near-fault ground motions. While these studies established the equivalence of response to actual ground motions and simple pulses, no appropriate record selection strategy or relevant observations were made other than the fact that pulse period is the most important parameter in the defining pulse motions.

Wavelet-analysis based pulses (Baker 2007; Mavroeidis and Papageorgiou 2003; Mukhopadhyay and Gupta 2013) have also been investigated to match more closely the actual velocity-time history of the near-fault earthquakes. These studies also established the importance of pulse period in the response to near-fault ground motions.

Simple single-cycle sinusoidal velocity pulses are implemented in this study to represent the near-fault earthquake ground motions. Simplicity of the shapes and the small number of parameters required to define the pulses allow for a comprehensive study of the response characteristics of these pulses. And the single cycle nature of these representative motions also ensures adequate representation of the impulsive characteristics of near-fault earthquake ground motions.

The proposed velocity pulses are defined in terms of the peak pulse velocity (V_p) and the pulse period (T_p.) The velocity time history over the duration of the pulse may thus be expressed mathematically as:

$$\dot{u}_\mathrm{p}(\mathrm{t}) = \mathrm{V_p} \sin\left(\frac{2\pi}{T_p}\mathrm{t}\right) \quad t \in [0, T_P] \tag{1}$$

Over the domain of the pulse duration, acceleration and displacement time histories of the pulse motion may be calculated by differentiating and integrating respectively the velocity time history. Obtained expressions may be written as:

$$\ddot{u}_\mathrm{p}(\mathrm{t}) = \frac{2\pi\,\mathrm{V_p}}{T_p}\cos\left(\frac{2\pi}{T_p}\mathrm{t}\right) \quad t \in [0, T_P] \tag{2}$$

$$u_\mathrm{p}(\mathrm{t}) = \frac{\mathrm{V_p} T_p}{2\pi}\left(1 - \cos\left(\frac{2\pi}{T_p}\mathrm{t}\right)\right) \quad t \in [0, T_P] \tag{3}$$

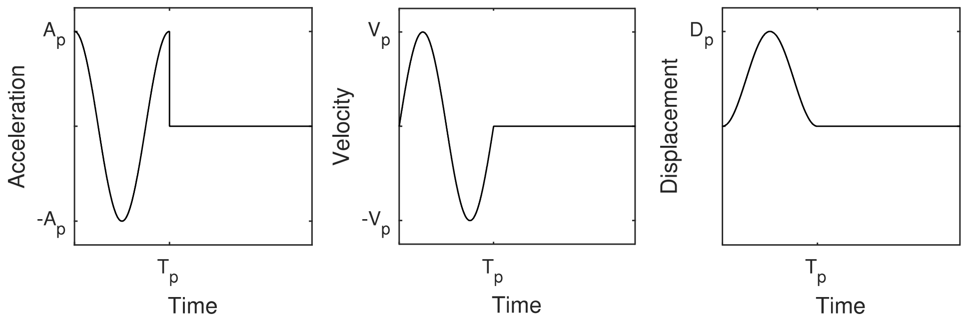

Figure 1 Acceleration (left,) velocity (middle,) and displacement (right) time history for a representative pulse motion with pulse period T_p. Vertical axis is not on the same scale for all three graphs.

A representation of pulse motions based on equations (1–3) is expressed in Figure 1. It must be noted that the assumuption of full cycle sinusoid in velocity time history results in different shapes in acceleration and displacement time histories, particularly the fact that the displacement time history is zero at the end of the cycle. This is particularly different from some previous studies (Suzuki et al. 2010; Yasui et al. 2010) that were based on full cycle sinusoid in acceleration time history which results in a non-zero displacement value at the end of the pulse cycle.

The peak acceleration (A_p) or displacement (D_p) value may also used for pulse definition instead of V_p. The peak quantities may be obtained directly from the pulse definition of equations 2 and 3 as follows:

$$A_p = \frac{2\pi \mathrm{V_p}}{T_p} \quad (4)$$

$$D_p = \frac{\mathrm{V_p} T_p}{\pi} \quad (5)$$

The input motions being used for evaluation are generated with varying pulse periods to understand the influence of pulse period on structural response. As defined by equations (1–3,) three sets of pulse motions can be generated with varying pulse period (T_p) and keeping the either of A_p, V_p, or D_p as constant. It must be noted that even while one of the peak quantities is kept constant the other peak quantities vary significantly with the varying pulse period.

3 Structural response analysis

In order to understand the influence of pulse-like ground motions, structural response of a single-degree-of-freedom system is studied in this section. Resposne analysis is carried out for linear elastic and bi-linear inelastic conditions. Response of a seismically isolated SDOF system is also studied. The following subsections describe in detail the system being evaluated for response, the response evaluation scheme and the observaions on the response to representative pulse motions.

3.1 Linear elastic response

Linear elastic response is evaluated for a single-degree-of-freedom system with damping at 5% of the critical. The governing equation of motion is solved numerically in MATLAB® using Newmark-β method with $\beta = 1/2$ and $\gamma = 1/6$.

Psuedo-acceleration, pusedo-velocity and displacement response spectrum are generated for the three sets of ground motions as expressed in the previous section. To understand the influence of pulse period (T_p) on the structural response, the spectral response quantities are plotted against normalized natural period (T_n/T_p.) A normalized natural period of 1 is thus representative of structures having natural period (T_n) same as the input motion pulse period (T_p.) The response spectrum plots thus generated are expressed in Figure 2.

As is evident from these response spectrum plots, the response to the pulse motions peaks for structures with T_n/T_p close to 1. But the exact peak is obtained slightly away from the T_n/T_p value of 1 and the peak location differs depending on the response quantity being considered. As expressed on the response spectrum plots for respective quantities, acceleration and velocity responses peak for T_n/T_p value less than 1 (at 0.76 and 0.89 respectively) while the displacement response peaks for T_n/T_p value greater than 1 (at 1.55.) This behavior can be explained on account of the impulsive nature of input pulse motions. Since the input motion is only a single cycle impulse, it is not sufficient to develop resonant response in the system. This can be comprehensively illustrated by considering response to input motions with multiple pulses. Figure 3 shows the response spectrum for pulse motions having increasingly greater number of cycles ranging from single-cycle pulse to five-cycle pulse. As the number of cycles in the input motions increase, the resonant response rapidly builds up and the peak moves closer to T_n/T_pvalue of 1 corresponding to a resonance response.

This observation is especially significant for the pulse motions with a larger pulse period (say 5 $sec.$) where response peak may be obtained for structures with significantly lower natural period ($0.76 \times 5 = 3.8\, sec.$) than the period of the ground motion pulse. This also highlights the significance of considering the near-fault effects for shorter period structures as due to the impulsive nature of the input, response of shorter period structures is critical. This observation also emphasizes the significance of studying impulsive near-fault ground motions as their response characteristics differ significantly from ordinary far-field ground motions in this context.

Another interesting observation from the set of response plots in Figure 1Figure 2 is the scaling of peak response values with input pulse period. For the set of input ground motions with common peak acceleration (A_p) the peak acceleration response comes out to be the same irrespective of the input pulse period. Similar observation is made in terms of peak velocity and displacement response for input ground motion sets with common V_p and D_p respectively.

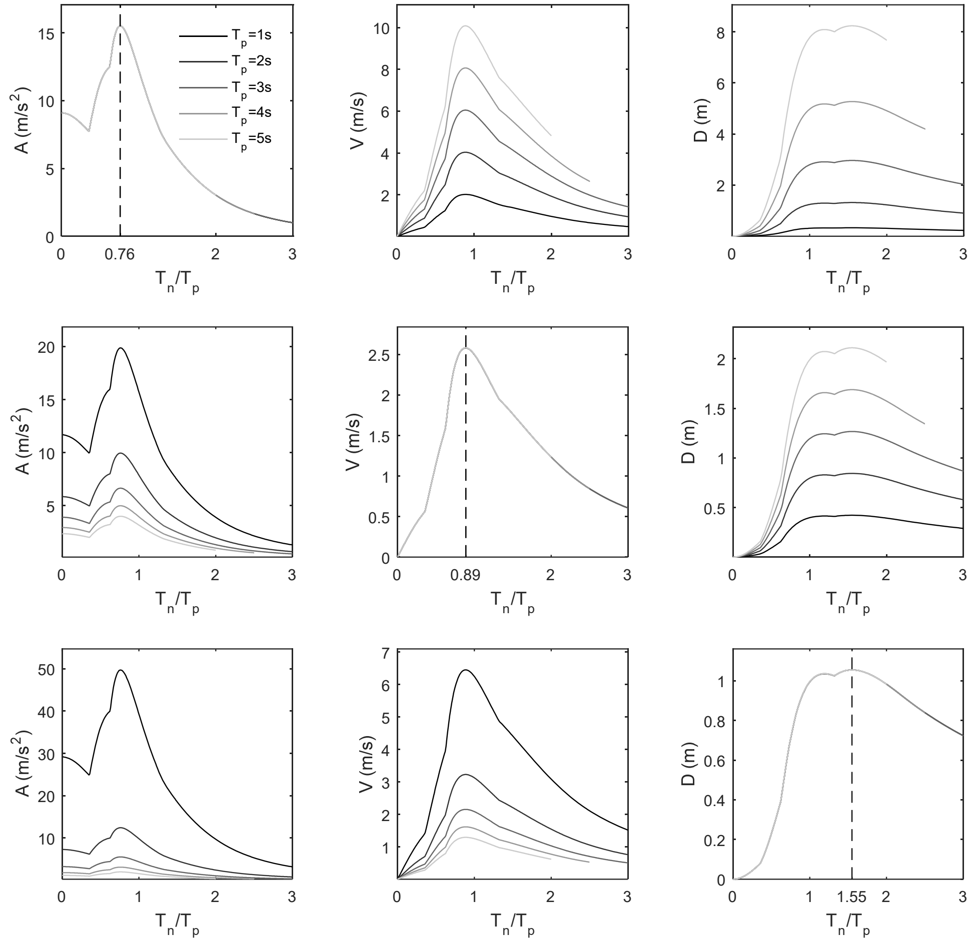

Figure 2 Psuedo-acceleration $(A,)$ pusedo-velocity $(V,)$ and displacement $(D,)$ response spectrum for pulse motions with vaying pulse periods (T_p) but contant peak acceleration (top row,) constant peak velocity (middle row,) and constant peak displacement (bottom row)

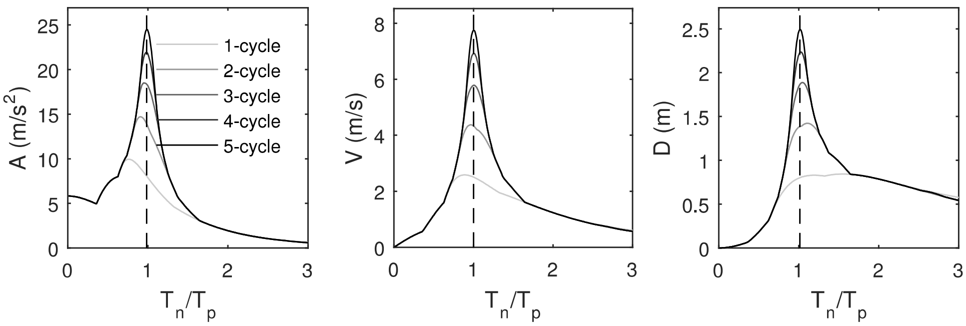

Figure 3 Response spectrum for pulse motions with multiple cycles of pulses but constant pulse period (T_p) and peak velocity (V_p)

It may also be noted that since the velocity response spectrum peak is obtained for T_n/T_p value away from 1, use of velocity response spectra of near-fault ground motions (Mavroeidis and Papageorgiou 2003; Alavi and Krawinkler 2004) for identification of pulse period (T_p) is error prone and may lead to a lower pulse period value. In light of this observation, use of the identified velocity pulse for pulse period determination may be more accurate (Baker 2007; Zhai et al. 2013.)

3.2 Bi-linear inelastic response

Bi-linear inelastic response is calculated for a single-degree-of-freedom system with post-yield stiffness taken as 5% of the elastic and damping at 5% of the critical. The governing equation of motion is solved numerically in MATLAB® using Newmark-β method with $\beta = 1/2$ and $\gamma = 1/6$.

Response is evaluated for the set of input motions described in Section 2. Yield force level of the bi-linear system is selected to obtain the displacement ductility (μ) as 5. Constant ductility response (acceleration, velocity and displacement) spectrum thus obtained are expressed in Figure 4. As explained in the discussion on elastic response, the response peaks are not obtained for T_n/T_p value of 1 owing to the impulsive nature of the input pulse. Interestingly though, the peaks for inelastic analysis are obtained at a lower value of T_n/T_p than what was observed for the linear elastic case. The response peaks for acceleration, velocity, and displacement are obtained for a T_n/T_p value of 0.55, 0.75, and 0.96 respectively which corresponds to a stiffer system compared to the one observed in the elastic case. Furhter, as observed in Figure 5, the constant ductility response spectrums generated for varying ductility levels also show this effect as all the response quantities are observed to peak for lower nomalized period with increasing target ductility.

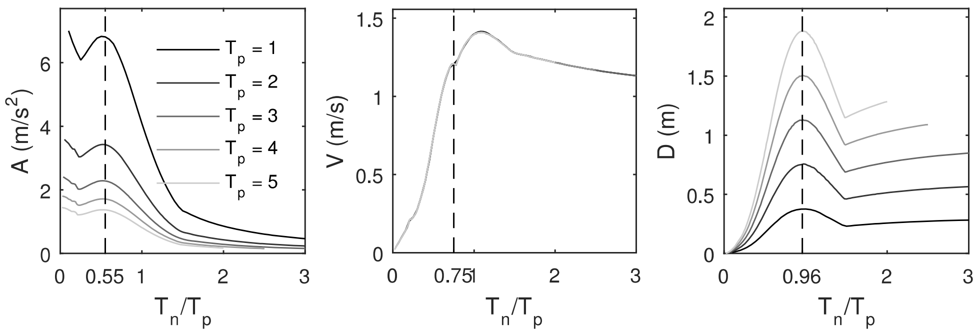

Figure 4 Constant ductility ($\mu = 5$) response spectrum for inelastic response to input pulse motions with varying pulse periods (T_p) but constant peak velocity ($V_p = 1\text{m/s}$)

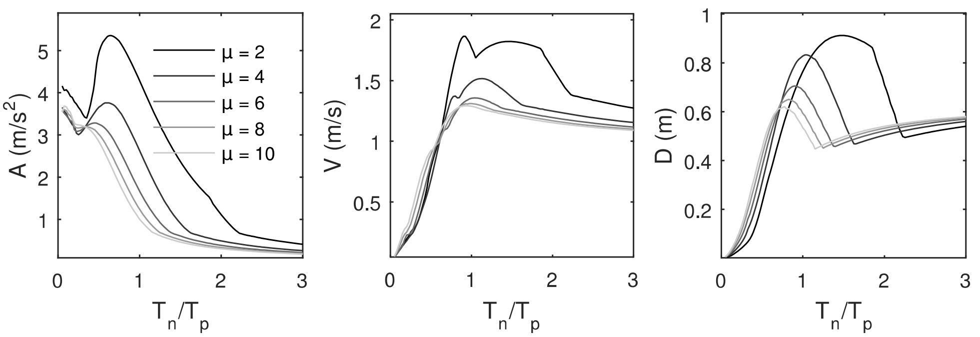

Figure 5 Constant ductility response spectrum for a pulse ground motion ($T_p = 2\text{s}, V_p = 1\text{m/s}$) evaluated at multiple ductility levels (μ)

3.3 Isolated system response

Long period phenomenon of near-fault earthquakes is expected be especially detrimental to the performance of seismically isolated structural systems owing to the long design periods of isolated systems. In this section, response of a single-degree-of-freedom system isolated with a friction pendulum system (FPS) (Zayas, Low, and Mahin 1990) against representative pulse motions is evaluated to gain an insight into the impulsive response characteristics of isolated systems.

Fundamental equations of motion for FPS (Mokha et al. 1991) are solved solved numerically in MATLAB® using Newmark-β method with $\beta = 1/2$ and $\gamma = 1/6$.

Acceleration, velocity and displacement response of the isolated structure evaluated for pulse motions with varying pulse periods. Unlike the response spectrum for a conventional SDOF system, response of the isolated system is calculated for a combination of natural peiod of the of the structure being isolated (T_n) and period of isolation of the FPS used for seismic isolation (T_b.) FPS is charaterized by friction coefficient (μ) at the sliding surface and radius of curvature (R) of the slidng surface. T_b is dependent solely on the R (Zayas, Low, and Mahin 1990) and is calculated as:

$$T_b = 2\pi\sqrt{\frac{R}{g}} \tag{6}$$

Response is calculated with μ as 0.08 while T_n and T_b being varied over to represent various structural configurations against pulse motions with constant pulse velocity ($V_p = 1\text{m/s}$) and varying pulse periods ($T_p = 1\text{s}$, 3s, and 5s.) Figure 6 expresses the calculated response as a contour plot against normalized T_b and T_n axes. Response values along the T_n/T_p axis at zero T_b/T_p represent the resposne of the SDOF system discussed previously in Section 3.1 on elastic response to pulse motions. Moving further along the vertical direction represents the resposne reduction or amplification offered by the isolator with corresponding isolator period T_b. For small T_b values, response amplification is observed over all T_n values as the isolation system is not really effective at small isolator periods. This amplification is especially significant around the T_n/T_p values for which peak response was observed in Section 3.1. Response amplification is also observed for T_b/T_p values close to 1 over T_n/T_p values ranging from 1.5 and above. Considerable reduction in response is however observed when the T_b/T_p values are larger than 2, even for the T_n/T_pvalues where the response was observed to peak in Section 3.1. This trend is observed in Figure 6 for either of the response quantities and is found to be equally valid for response to pulse motions with all pulse periods (T_p.)

4 Conclusion

Near-fault pulse motions have been observed to induce peculiar response in structures due to the impulsive characteristics of the input. Major observations for elastic, inelastic and isolated structure response may be expressed as follows:

- Response to given pulse motions is more crucial for structures with natural period less than the pulse period (not the structures with same natural period as the period of the input pulse as the resonance phenomenon would suggest.)
- Acceleration, velocity and displacement responses peak for different structural natural period (T_n) given the same input pulse motion.
- Inelastic response to pulse motions peaks for different structural natural period (T_n) depending on the level of the target ductility (μ.)
- Isolation systems designed with an isolator period (T_b) close to T_p are ineffective in reducing strucural response but an isolator designed with T_b in a higher period range can result in considerable response reduction even for structural systems with T_n close the pulse period T_p.

Based on these observations, important considerations from the point of view of record selection and strucute design for near-fault zones may be outlined as follows:

- *Pulse period and response parameter*: Given the sensitivity of structural response to the ratio of structural period to pulse period (T_n/T_p,) selection of ground motions with appropriate pulse period is crucial. This selection is further influenced by the choice of response quantity being evaluated as acceleration, velocity, and displacement peak for widely different values of T_n/T_p .
- *Target ductility*: The level of target ductility that the system is designed for should also be taken into account for record selection. Response to the same ground motion pulse peaks for a stiffer system as the target ductility is increased.

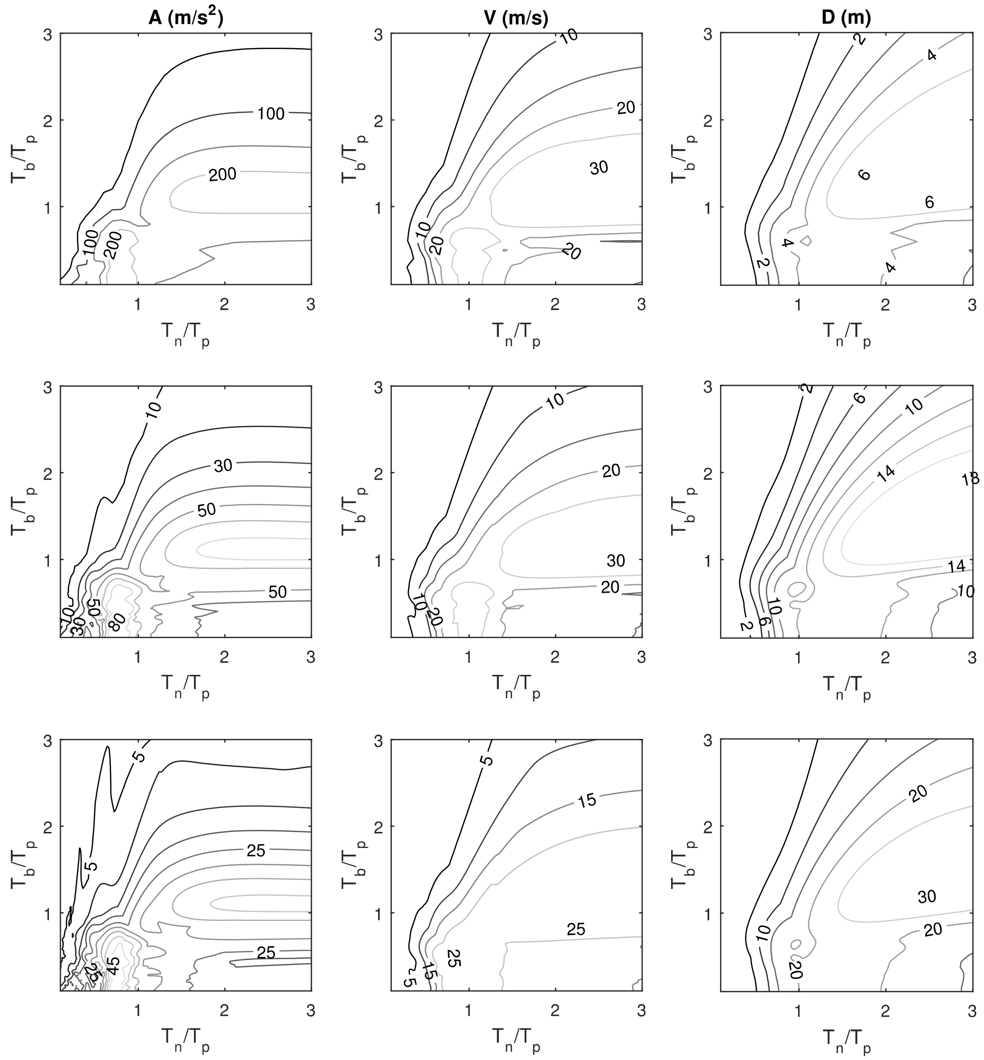

Figure 6 Response spectrum plots of an isolated system (period of isolation, T_b) for input pulse motions ($V_p = 1\mathrm{m/s}$) with varying pulse periods ($T_p = 1\mathrm{s}$, top row; $T_p = 3\mathrm{s}$, middle row; $T_p = 5\mathrm{s}$, bottom row) and varying period of isolation (T_b)

References

Alavi, Babak, and Helmut Krawinkler. 2004. "Behavior of Moment-Resisting Frame Structures Subjected to near-Fault Ground Motions." *Earthquake Engineering & Structural Dynamics* 33 (6): 687–706.

Attalla, Mourad R., Terrence F. Paret, and Sigmund A. Freeman. 1998. "Near-Source Behavior of Buildings under Pulse-Type Earthquakes." In *Proceedings of the 6th U.S. National Conference on Earthquake Engineering*.

Baker, J. W. 2007. "Quantitative Classification of Near-Fault Ground Motions Using Wavelet Analysis." *Bulletin of the Seismological Society of America* 97 (5): 1486–1501. doi:10.1785/0120060255.

Makris, Nicos, and Shih-Po Chang. 2000. "Response of Damped Oscillators to Cycloidal Pulses." *Journal of Engineering Mechanics* 126 (2): 123–131.

Mavroeidis, George P., and Apostolos S. Papageorgiou. 2003. "A Mathematical Representation of near-Fault Ground Motions." *Bulletin of the Seismological Society of America* 93 (3): 1099–1131.

Mokha, Anoop, M. C. Constantinou, A. M. Reinhorn, and Victor A. Zayas. 1991. "Experimental Study of Friction-Pendulum System." *Journal of Structural Engineering* 117 (4): 1201–17.

Mollaioli, Fabrizio, Silvia Bruno, Luis D. Decanini, and Giuliano F. Panza. 2006. "Characterization of the Dynamic Response of Structures to Damaging Pulse-Type Near-Fault Ground Motions." *Meccanica* 41 (1): 23–46. doi:10.1007/s11012-005-7965-y.

Mukhopadhyay, Suparno, and Vinay K. Gupta. 2013. "Directivity Pulses in near-Fault Ground motions—I: Identification, Extraction and Modeling." *Soil Dynamics and Earthquake Engineering* 50 (July): 1–15. doi:10.1016/j.soildyn.2013.02.017.

Sasani, Mehrdad. 2006. "New Measure for Severity of Near-Source Seismic Ground Motion." *Journal of Structural Engineering* 132 (12): 1997–2005. doi:10.1061/(ASCE)0733-9445(2006)132:12(1997).

Sasani, Mehrdad, and Vitelmo V. Bertero. 2000. "Importance of Severe Pulse-Type Ground Motions in Performance-Based Engineering." In *Proceedings of the 12th World Conference on Earthquake Engineering*. http://www1.coe.neu.edu/~sasani/pubs/C2.pdf.

Suzuki, Kyohei, Hidenori Kawabe, Masumi Yamada, and Yasuhiro Hayashi. 2010. "Design Response Spectra for Pulse like Ground Motions." *AIJ Journal of Structural and Construction Engineering* 75 (647): 49–56. doi:10.3130/aijs.75.49.

Yasui, Masaaki, Taketomo Nishikage, Tomohiro Mikami, Isao Kamei, Kyohei Suzuki, and Yasuhiro Hayashi. 2010. "Theoretical Solutions and Response Properties of Maximum Response of a Single-Degree-of-Freedom System for Pulse-Wave Ground Motions." *AIJ Journal of Structural and Construction Engineering* 75 (650): 731–39. doi:10.3130/aijs.75.731.

Zayas, Victor A, Stanley S Low, and Stephen A Mahin. 1990. "A Simple Pendulum Technique for Achieving Seismic Isolation." *Earthquake Spectra* 6 (2): 317–33.

Zhai, C., Z. Chang, S. Li, Z. Chen, and L. Xie. 2013. "Quantitative Identification of Near-Fault Pulse-Like Ground Motions Based on Energy." *Bulletin of the Seismological Society of America* 103 (5): 2591–2603. doi:10.1785/0120120320.