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SIGNAL PROCESSING AND PROBABILISTIC SEISMIC HAZARD ANALYSIS TOOLS FOR CHARACTERIZING THE IMPACT OF NEAR-FAULT DIRECTIVITY

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Abstract: Near-fault ground motions containing strong velocity pulses are of interest to engineers designing systems close to active faults. These ground motions, which are here referred to as 'pulse-like ground motions,' have been identified as imposing extreme demands on structures, but methods of accounting for their effects in design are still relatively ad hoc. This paper reviews a recently proposed quantitative ground motion classification system that is being utilized to identify these ground motions, study their unique effects on structures, and account for their occurrence in probabilistic seismic hazard analysis. Example results are shown to illustrate the classification scheme, how it can be used to develop statistical models that predict the occurrence and severity of this effect in future ground motions, and what impact these models have on probabilistic seismic hazard analysis calculations.

1. INTRODUCTION

Pulse-like near-fault ground motions resulting from directivity effects are a special class of ground motions that are particularly challenging to characterize for seismic performance assessment. These motions contain a 'pulse' in the velocity time history of the motion, typically in the direction perpendicular to the fault rupture, and generally occur at locations near the fault where the earthquake rupture has propagated towards the site. It has been observed that these motions have, on average, larger elastic spectral acceleration values at moderate to long periods. Additionally, these motions tend to cause severe response of nonlinear multi-degree-of-freedom structures to an extent not entirely accounted for by measuring the intensity of the ground motion using spectral acceleration at the elastic first-mode period of a structure. Despite our growing understanding of these ground motions, many questions remain when trying to incorporate these effects into design codes. How can one distinguish between 'pulse-like' and ordinary ground motions, other than through a visual identification that relies on user judgment? How should directivity effects be accounted for when determining the target ground motion intensity level used for design? If one is performing dynamic analysis of the structure, what fraction of input ground motions should have directivity pulses, given that not all near-fault ground motions contain pulses? Should the ground motions be input in a 'worse case' fault-normal/fault-parallel orientation, or is some other orientation more appropriate?

Forward directivity results when the fault rupture propagates towards the site at a velocity nearly equal to the propagation velocity of the shear waves and the direction of fault slip is aligned with the site. This causes the wave front to arrive as a single large pulse. Forward directivity effects in the near-fault region can cause large-amplitude pulses that occur early in the velocity time history. A more detailed description of this phenomenon is given by, e.g., Somerville et al. (1997). For both strike-slip and dip-slip faults, forward directivity typically occurs in approximately the fault normal direction, although this is not always the case. Another near-fault effect, fling step, is mentioned for completeness but not considered here. This permanent displacement of the ground resulting from fault rupture can be important for structures such as lifelines crossing a fault, but is less important for general structural design than the effects of directivity.

This paper summarizes recent work in ground motion processing and seismic hazard analysis that facilitates the incorporation of directivity effects into the widely used probabilistic seismic hazard analysis (PSHA) procedure. This work is then used to perform an example PSHA for a near-fault site with and without accounting for directivity effects, to examine the impact of directivity. The results are used to illustrate how the above questions can be answered in a systematic manner, and to speculate as to how near-fault factors might be incorporated into building codes in a more systematic manner. These results are also compared to previous results using the widely used model of Somerville et al. (1997), and the distinctions and advantages of the approach used here are described.

2. WAVELET-BASED GROUND MOTION ANALYSIS AND PULSE EXTRACTION

Directivity pulses are known to occur in near-fault ground motions, but the presence and severity varies due to variations in source properties and source-to-site geometry (which affects the constructive interference of seismic waves as they propagate towards the site of interest). For this reason, it is not always clear whether a particular near-fault ground motion contains a velocity pulse; see Figure 1 for example ground motions having velocity pulses of varying severity.

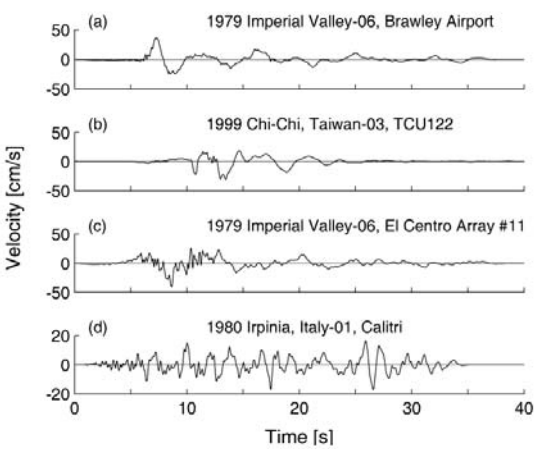


Figure 1. Example fault-normal near-fault ground motions (from Baker 2007).

Several researchers have developed detailed analytical models describing the shapes of velocity pulses resulting from directivity (Fu and Menun 2004; Makris and Black 2004; Mavroeidis and Apostolos S. Papageorgiou 2003; Rodríguez-Marek and Bray 2004). These models are useful when specifying dynamic loading for parametric studies of structural response to velocity pulses. A critical component of these models is the period, or frequency, of the velocity pulse. This pulse period has been seen to be correlated with the magnitude of the causative earthquake (Bommer et al. 2001; Mavroeidis and Apostolos S. Papageorgiou 2002; Somerville 2003). None of these models, however, is able to determine whether an arbitrary ground motion contains a pulse; they are only used to characterize pulses that have previously been identified by user judgment.

To empirically determine the probability of observing a directivity pulse under a given set of conditions, it is necessary to classify an existing library of near-fault ground motions according to whether or not they contain a pulse. Typically, users classify records manually using their best visual judgment, but this results in classifications that vary from author to author (Fu and Menun 2004; Mavroeidis and Apostolos S. Papageorgiou 2003; Somerville 2003; Akkar et al. 2005; Cox and Ashford 2002). Relying on user judgement is also time consuming when processing large ground motion libraries. For a quantitative classification procedure to be effective, several criteria are important. First, the procedure should be able to distinguish between pulse-like and ordinary ground motions. Additionally, the classification procedure should require minimal intervention or judgment from the analyst and should produce a reproducible result so that classifications of a given ground motion are consistent from analyst to analyst. A computationally inexpensive procedure is also preferable, because thousands of recorded ground motions will need to be processed. The authors have recently developed a classification concept that uses wavelet-based signal processing to identify and extract the largest velocity pulse from a ground motion (Baker 2007). If the extracted pulse is 'large' relative to the remaining features in the ground motion, the ground motion is classified as pulse-like. Quantitative descriptions of pulse amplitude are produced using the proposed technique, so there is a precise definition of a 'large pulse.' The period of the detected velocity pulse, a needed parameter for the proposed assessment approach, is also easily determined. The algorithm requires only a few seconds to analyze and classify a given ground motion.

The proposed classification technique utilizes wavelet analysis, as illustrated schematically in Figure 2. Similar to a Fourier Transform, which decomposes a signal into a set of sine and cosine waves, the wavelet transform decomposes the signal into a series of "wavelets." In Fourier analysis, the sine and cosine waves serve as basis functions; each wave is very precise in terms of the frequency it represents, but not at all precise in the time range it represents (because it is infinite in length). In contrast, a wavelet basis function is somewhat precise in both the time and frequency range it represents. This time localization is particularly advantageous when studying short-duration phenomena such as directivity pulses. As seen in Figure 2, a single wavelet can substantially represent the strongest velocity pulse present in the example ground motion. This efficient representation of short-duration pulses makes the wavelet transform an ideal mathematical tool for identifying and analyzing the presence of strong velocity pulses.

Figure 3 illustrates further how the wavelet decomposition of a signal can be used to detect velocity pulses. The first panel of this figure illustrates the original ground motion velocity time history, along with the wavelet having the largest amplitude (which again identifies the strong velocity pulse). The second panel shows the identified velocity pulse, which consists of the largest wavelet, plus several additional wavelets having the same frequency and located adjacent in time to the original wavelet. The third panel shows the residual ground motion, obtained by subtracting the pulse from the original ground motion. This decomposition can be performed for any ground motion, as some wavelet is always the largest. So, in order to classify a ground motion as pulse-like, the residual ground motion is compared to the original ground motion to see if the intesity of the motion has decreased significantly (in terms of its energy and peak ground velocity). Baker (2007) provides a quantitative measure of this comparison that can be used toclassify any ground motion.

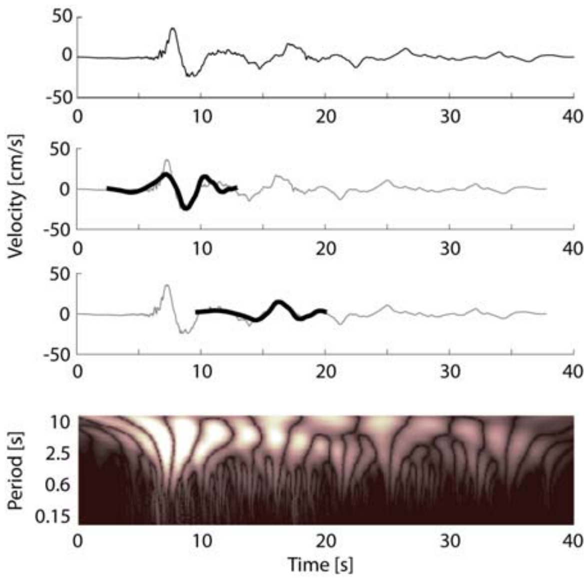


Figure 2. Example results for the wavelet decomposition of a velocity time history. The top panel shows the original time history. The second panel shows the largest single wavelet coefficient that appears in the ground motion (which typically matches the large velocity pulse in the ground motion, if one is present). The third panel shows the largest remaining wavelet coefficient if the first coefficient is removed from the time history. The final panel shoss the continuous wavelet transform coefficients for all periods and locations in the time history(light shading indicates a large absolute value of the coefficient with the specified period and location in time).

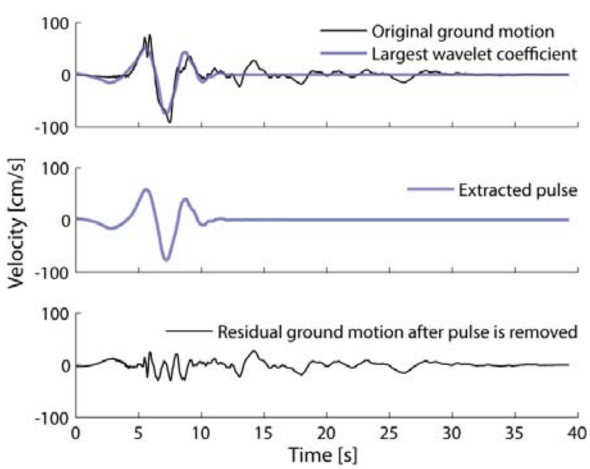
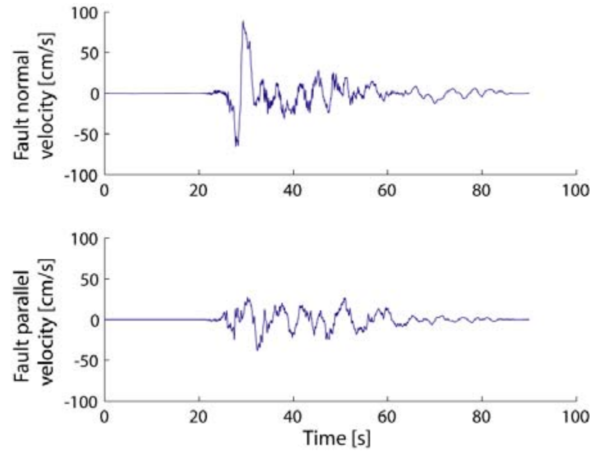
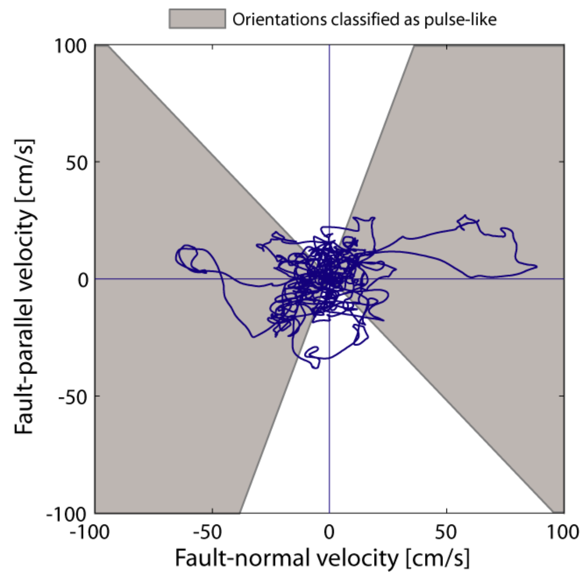


Figure 3. Illustration of the proposed decomposition procedure used to extract the pulse portion of a ground motion. (from Baker 2008).



(a)



(b)

Figure 4. Velocity time history of the Chi-Chi, Taiwan, Tsaotun (TCU075) ground motion. (a) Fault normal and fault parallel velocity time histories. (b) Fault normal versus fault parallel velocity, with shaded regions denoting orientations classified as pulse-like using the proposed procedure (adapted from Baker 2007).

The classification procedure that has been described thus far is applicable to individual components of a ground motion. But the procedure can be applied to multi-component ground motions that have been rotated to arbitrary orientations, to see the range of orientations over which a strong pulse is present. Figure 4a shows the fault normal and fault parallel components of an example ground motion, illustrating a strong pulse in the fault normal direction but not in the fault parallel direction (as theory would suggest should be the case). The ground motions velocity profile is plotted in two dimensions in Figure 4b, showing the large velocity pulse orientied largely in the fault normal direction. But by rotating the ground motion to other orientations, we can repeatedly re-classify it, and identify the range of orientations over which the pulse is strong. This range of orientations is denoted by the shading in Figure 4b. Ongoing research by the authors suggests that velocity pulses are often very clear over a wide range of orientations, and that the strongest orientation is not always fault normal. This emperical finding is justified theoretically by noting that "fault normal" is somewhat of an abstraction for non-planar ruptures, and by noting that variability in the rupture and wave-propagation path may disrupt primary orientations of directivity effects.

3. Seismic hazard analysis

Basic calculations have been performed to evaluate the effects of directivity on seismic hazard analysis (Abrahamson 2000). This work has utilized the simple response spectrum modification of Somerville et al. (1997) discussed in the previous section. Abrahamson (Abrahamson 2000) found that, as expected, directivity effects increased the ground motion intensity associated with a given return period at sites located near active faults. But because only a simple spectrum modification was used, this approach provides no information regarding the period of the pulses responsible for the increased ground motion intensity. As seen in the previous section, this pulse period is important when estimating structural response and thus it is important to consider when selecting ground motions for use in dynamic structural analysis. Tothong et al. (2007) have recently proposed a new framework for seismic hazard analysis that can include pulse periods explicitly, and has thus been modified and calibrated for implementation as part of this work.

Once the pulse-like ground motions have been identified, their effects can be incorporated into probabilistic seismic hazard analysis. The technique adopted by the authors is adapted from that proposed by Tothong et al. (2007). Some highlights are provided here. For reference, let us first consider the standard Probabilistic Seismic Hazard Analysis calculations (for more details see, e.g., Kramer 1996; McGuire 2004). Without loss of generality, we can consider the case with one seismic source as follows

$$\nu_{S_a}(x) = \nu_{eq} \iint_{m,r} P(Sa > x \mid m,r)\, f(m,r)\, dm\, dr \qquad (1)$$

where $\nu_{S_a}(x)$ is the annual rate of spectral acceleration at a given period (*Sa*) exceeding *x*, ν_{eq} is the annual rate of earthquakes on the source, $P(Sa > x \mid m,r)$ is the probability that spectral acceleration at the given period exceeds *x* given an earthquake with magnitude *m* and distance *r* (as characterized by standard ground motion prediction models), and $f(m,r)$ is the joint probability density function of *m* and *r*. The integration over *m* and *r* is an application of the total probability theorem.

To consider near-fault directivity, equation (1) is modified as follows

$$\nu_{S_a}(x) = \nu_{eq} \iiint_{m,r,z} P^*(Sa > x \mid m,r,z)\, f(m,r,z)\, dm\, dr\, dz \qquad (2)$$

where *z* is a new parameter or vector of parameters describing source-to-site geometry properties that predict occurrence of near-fault velocity pulses, $P^*(Sa > x \mid m,r,z)$ is an updated ground motion prediction model that accounts for possible directivity pulses as a function of *z*, and $f(m,r,z)$ is the joint probability density function for *m*, *r* and *z*. Implementation of this model requires the updated prediction model $P^*(Sa > x \mid m,r,z)$, and the identification and characterization of the parameter(s), *z*, that are effective in predicting occurrence of velocity pulses.

The updated prediction model can be constructed from a variety of existing models along with modification functions, so that the considerable body of knowledge that was used to create an existing ground motion model can be retained. The updated model can be formulated using the Total Probability Theorem as follows:

$$\begin{aligned} P^*(Sa > x \mid m,r,z) &= P(Pulse \mid z) P_{Pulse}(Sa > x \mid m,r,z) \\ &\quad + \left(1 - P(Pulse \mid z)\right) P(Sa > x \mid m,r) \end{aligned} \qquad (3)$$

where $P(Pulse \mid z)$ predicts the probability of observing a pulse-like ground motion, given a source-to-site geometry parameterization defined by *z* (e.g., Iervolino and Cornell 2008). $P_{Pulse}(Sa > x \mid m,r,z)$ is a ground motion prediction for pulse-like ground motions, which here is assumed to consist of a standard ground motion prediction model plus a "pulse amplification function" that increases predicted ground motions to account for the effect of the velocity pulse; this function assumes occurrence of a pulse (as this occurrence is accounted for by the $P(Pulse \mid z)$ term), and amplifies spectral amplitudes in some range around the pulse period (e.g., Baker 2008; Shahi and Baker 2010). This requires a predictive model for pulse periods, which is available from several sources (Baker 2007; Bray and Rodríguez-Marek 2004; Mavroeidis et al. 2004; Somerville 2003). The new predictive models have been termed "narrow-band" in that they are dependent upon the period of the pulse rather than amplifying all periods due to pulse effects (Somerville 2003).

Non-pulse-like ground motions are accounted for in the second term of the summation of equation (3). Currently, the $P(Sa > x \mid m,r)$ predictions for non-pulse-like ground motoins are assumed to be reasonably predicted by standard ground motoin prediction models, but ongoing work is investigating whether that prediction might be overly conservative, as standard ground motion prediction models are calibrated using both pulse-like and non-pulse-like ground motions, while this model should represent only non-pulse-like motions (which presumably have lower intensities).

While further mathematical details of the calibration and combination of these models is omitted here for brevity, they are available from other sources (Shahi and Baker 2010; Tothong et al. 2007). Another portion of the mathematical details of this calculation whose details are omitted is the deaggregation of input parameters, conditional upon exceeding a given spectral acceleration intensity. Deaggregation on magnitude, distance and ε can be performed as with standard PSHA, but now it is also possible to deaggregate on directivity parameters. Conditional upon exceedance of a spectral acceleration threshold, it is possible to compute the associated probability of observing a velocity pulse and the distribution of pulse periods.

4. Example analysis

Using the framework and predictive models cited in the previous section, an example analysis can be performed to highlight the impact of considering near-fault directivity. The geometry of the example site considered is illustrated in Figure 5, and is further quantified by the following parameters. The single fault in the region has a truncated Gutenberg-Richter distribution of earthquake magnitudes (with a minimum magnitude of five and maximum magnitude of seven). The Gutenburg-Richter "b-value" is 0.9. The site being considered is located 6.7 km from the fault and has an average shear-wave velocity over the top 30 meters (V_{s30}) of 250 m/s. These choices were made to approximately represent conditions of the Imperial Valley Fault in Southern California, and the El Centro Array #4 station that experienced a strong velocity pulse in the 1979 Imperial Valley earthquake.

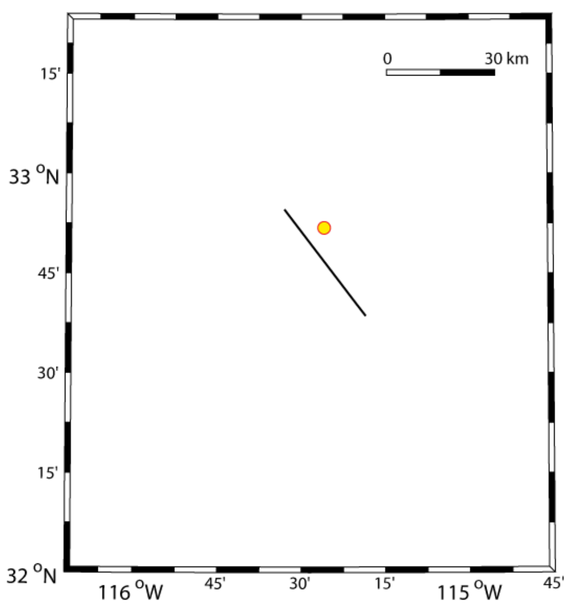


Figure 5. Map of fault and site geometry the example analysis.

Using this information PSHA was performed using three techniques, and 2% in 50 years uniform hazard spectra (UHS) for the site are shown in Figure 6. The analysis was first performed using the standard PSHA equation of equation (1). The second analysis was performed using the proposed PSHA equation given in equation (2). For reference, the PSHA approach proposed by Abrahamson (2000), using the ground motion prediction model adjustment by Somerville et al. (1997), is also shown in the figure. While the Somerville prediction model always gives directivity amplifications that increase monotonically with period, the proposed technique has amplifications with period that depend upon the earthquake magnitudes most likely to cause strong ground shaking at the site. In this case, the uniform hazard spectrum is dominated by earthquakes with magnitudes close to seven, causing the amplification model to amplify periods near two seconds by the greatest amount. In this analysis, the proposed PSHA approach causes spectral values at two seconds to be amplified by 13% relative to the corresponding UHS value obtained without explicit directivity considerations. It should be noted that these exact numerical values are still tentative. Further refinement of the amplification model, and a more comprehensive study of PSHA analysis, are expected to lead to more precise and more general results of this type in the near future.

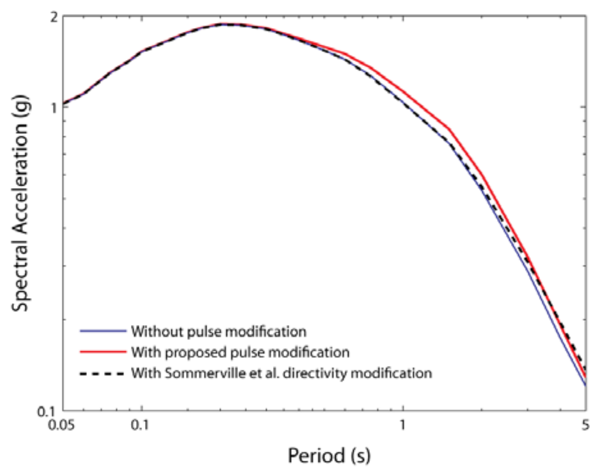


Figure 6. Uniform hazard spectra with 2% probability of exceedance in 50 years, obtained for the example site using three Probabilistic Seismic Hazard Analysis techniques.

5. CONCLUSIONS

This paper has highlighted some recent progress in ground motion pulse classification, seismic hazard analysis, and ground motion intensity predictions that facilitate a new quantitative approach for assessing the potential effects of these ground motions. Bringing these tools together will help engineers and seismologists more fundamentally understand the effect of this phenomenon, and will give stakeholders greater confidence that projects are being designed using rational tools to account for all effects of ground shaking. A more quantitative representation of pulses, pulse occurrence, and their effect on structural response will also be useful to seismologists working on simulation of synthetic ground motion time histories. These new models will provide target results and a better understanding of important ground motion properties for seismologists to use in validation of their simulations.

Some major features of the proposed signal processing and hazard analysis approach have been presented here. It is hoped that this brief overview will present some important characteristics of the technique, and point interested readers towards other references providing more mathematical details (Baker 2007; Shahi and Baker 2010; Tothong et al. 2007).

The effort described here will result not only in new models to address the impacts of near-fault velocity pulses, but also in a variety of software tools and data sets to support extension and application of this work by other researchers and practitioners. Relevant signal processing software and example analysis results are currently available at *http://stanford.edu/~bakerjw/pulse-classification.html*. These offerings will continue to be updated and expanded as refined analysis models are developed.

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