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Simulation of Strong Ground Motions for Seismic Fragility Evaluation of Nonstructural Components in Hospitals

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Technical Report MCEER-05-0005

May 26, 2005

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NOTICE

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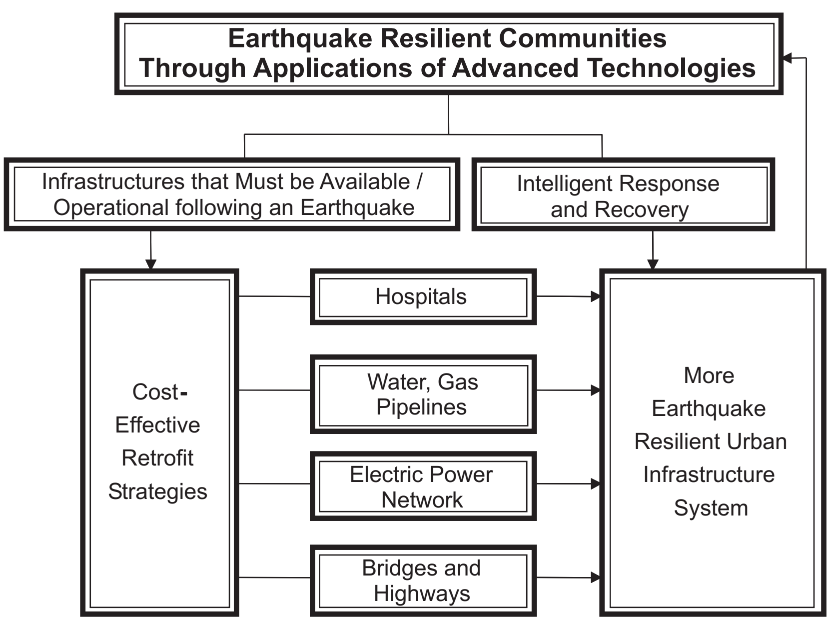
Preface

The Multidisciplinary Center for Earthquake Engineering Research (MCEER) is a national center of excellence in advanced technology applications that is dedicated to the reduction of earthquake losses nationwide. Headquartered at the University at Buffalo, State University of New York, the Center was originally established by the National Science Foundation in 1986, as the National Center for Earthquake Engineering Research (NCEER).

Comprising a consortium of researchers from numerous disciplines and institutions throughout the United States, the Center's mission is to reduce earthquake losses through research and the application of advanced technologies that improve engineering, pre-earthquake planning and post-earthquake recovery strategies. Toward this end, the Center coordinates a nationwide program of multidisciplinary team research, education and outreach activities.

MCEER's research is conducted under the sponsorship of two major federal agencies: the National Science Foundation (NSF) and the Federal Highway Administration (FHWA), and the State of New York. Significant support is derived from the Federal Emergency Management Agency (FEMA), other state governments, academic institutions, foreign governments and private industry.

MCEER's NSF-sponsored research objectives are twofold: to increase resilience by developing seismic evaluation and rehabilitation strategies for the post-disaster facilities and systems (hospitals, electrical and water lifelines, and bridges and highways) that society expects to be operational following an earthquake; and to further enhance resilience by developing improved emergency management capabilities to ensure an effective response and recovery following the earthquake (see the figure below).



A cross-program activity focuses on the establishment of an effective experimental and analytical network to facilitate the exchange of information between researchers located in various institutions across the country. These are complemented by, and integrated with, other MCEER activities in education, outreach, technology transfer, and industry partnerships.

This report provides ensembles of simulated ground motions representative of scenario earthquake events for hypothetical hospital sites on the west and east coasts of the United States. The standardized accelerograms generated have four different hazard levels: 2%, 5%, 10% and 20% probabilities of exceedance in 50 years. A fault configuration similar to the Santa Susana fault in Northridge, California was selected as the prototype configuration for simulating the west coast accelerations. For each hazard level, 25 fault-normal and 25 fault-parallel horizontal accelerations with 25 corresponding vertical accelerograms were generated. Correspondingly for the east coast, two ensembles of earthquakes were simulated, i.e., a short ensemble which contains 50 earthquakes for each hazard level (50 fault-normal and 50 fault-parallel horizontal accelerations and 50 vertical ground motions) and a long ensemble which contains 100 simulated accelerograms in each ensemble. These simulated earthquakes will be used as input to develop analytical and experimental fragility curves of nonstructural components contained in acute care facilities.

ABSTRACT

The study presented herein discusses the methodology used to simulate ensembles of strong ground motions representative of scenario earthquake events for hypothetical hospital sites on the west coast and east coast of the United States. These simulated ground motions will be used in the MCEER Hospital Project (Thrust Area 2) to develop analytical and experimental fragility curves of nonstructural components contained in acute care facilities. The standardized accelerograms are generated for four different hazard levels: 2%, 5%, 10%, and 20% probabilities of exceedance of pseudo-spectral acceleration (PSA) in 50 years. The methods used in the simulation of the horizontal and vertical ground motions are presented. For each earthquake event, three acceleration components are simulated, i.e., fault-normal and fault-parallel horizontal components, and the corresponding vertical acceleration.

ACKNOWLEDGMENTS

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Any opinions, findings, conclusions, and recommendations presented in this reports are those of the authors and do not necessarily reflect the views of the sponsors.

The authors gratefully acknowledge Professor Apostolos Papageorgiou, Dr. Benedikt Halldorsson, and Dr. George Mavroeidis for providing the Specific Barrier Model, as well as the simulation procedures and the corresponding software, for this study and for sharing their expertise during this project.

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SECTION 1
INTRODUCTION

This report presents the procedures used to simulate ensembles of ground motions for two specific hospital sites on the west coast and east coast of the United States. The research was carried out as part of MCEER's Seismic Retrofit of Acute Care Facilities research area, known as Thrust Area 2. This research seeks to develop a better understanding of the applications of various seismic response modification technologies to protect structural and nonstructural systems and components in acute care facilities from the effects of earthquakes. The research effort is fully described in Aref et al., 2004.

To standardize the earthquakes used in analyses, accelerograms with four different probabilities of exceedance; i.e., 2%, 5%, 10%, and 20% probability of exceedance in 50 years, are generated.

The stochastic modeling approach (see e.g., Boore 1983, 2003) is applied to simulate the incoherent (high-frequency) part of the strong ground motions. The Specific Barrier Model (SBM) proposed and developed by Papageorgiou and Aki (1983a, 1983b) is adopted to describe the earthquake source, based on the recent calibration of the SBM by Halldorsson and Papageorgiou (2005). For sites in the "near-fault" region, the methodology introduced and presented by Mavroeidis and Papageorgiou (2003) is applied to synthesize low-frequency velocity pulses. Due to the different characteristics of earthquakes on the west and east coasts of the United States, different generation procedures are applied, as discussed in later sections.

The vertical ground motions corresponding with the simulated horizontal earthquakes are generated based on the response spectra of the corresponding horizontal accelerograms. Finally, two horizontal components, i.e., fault-normal and fault-parallel components, and one vertical component of synthetic ground motions, are generated at the site for each scenario earthquake event.

This report has seven sections. Section 2 introduces the model used in the simulation procedure. Sections 3 and 4 present the selection of scenario earthquake events and the corresponding strong motion simulations for the west and east coast sites, respectively. Section 5 describes the generation of the vertical accelerations, followed by conclusions and references in Sections 6 and 7, respectively. The appendices provide accelerograms and response spectra for both the west and east coast sites, and the simulated strong ground motions are provided on an accompanying CD.

SECTION 2
SIMULATION OF STRONG GROUND MOTIONS USING THE SPECIFIC BARRIER MODEL

The most expedient and computationally efficient method for simulating strong ground motion is the *stochastic modeling approach*, which is based on the assumption that accelerograms are realizations of a stochastic process with time varying intensity and, possibly, frequency content. The intent of the stochastic modeling approach is to capture the essential characteristics of high-frequency (higher than ~1 Hz) strong ground motions that are to be expected at an average site at a distance r from an average earthquake event of a specified magnitude, M.

The early developments related to the stochastic modeling of accelerograms came about thanks primarily to the efforts of the engineering community. Not having a physical model to describe the frequency content of the elastic waves radiated by the earthquake source, earthquake engineers adopted simple and/or empirical spectral models (e.g., white noise spectrum, Kanai-Tajimi spectrum; see for example Clough and Penzien, 1993 for a review of stochastic models; or see Shinozuka and Deodatis, 1988 for a review of ground motion). Seismologists, recognizing the stochastic character of high-frequency waves, made an important contribution to the developments related to the stochastic modeling approach by using a physical *seismological* model (instead of an empirical one) to describe the spectral content of the simulated motions (Hanks, 1979; Hanks and McGuire, 1981; Boore, 1983). A seismological model estimates, in terms of spectral scaling, the seismic motion at a site as a function of source strength, anelastic and geometric attenuation of seismic waves due to propagation path effects between the source and the site, as well as wave amplification due to site effects.

The source description (source spectrum) and its scaling with earthquake size is the most important part of the seismological model. Although it is now widely recognized that the high-frequency radiation from an earthquake source is controlled by heterogeneities on the fault plane (see e.g., Papageorgiou, 2003), most studies have assumed the simple "ω-square" model using Brune's (1970, 1971) source scaling (see e.g., Boore, 2003). The *specific barrier model* (SBM), proposed and developed by Papageorgiou and Aki (1983a, b) for the quantitative description of heterogeneous rupture is a much more physically realistic description of the earthquake source and is fully consistent with the salient features of more complex theoretical models of rupture and observed source spectra. Furthermore, it provides the most complete, yet parsimonious, self-consistent description of the faulting processes that are responsible for the generation of high-frequency waves, and it applies both in the "near-fault" as well as in the "far-field" region, which allows for consistent ground motion simulations over the entire frequency range and for all distances of engineering interest (see e.g., Papageorgiou, 2003; Halldorsson, 2004). The SBM has recently been calibrated based on strong motion data from three regions of different tectonic characteristics: *Interplate* (earthquakes on or close to plate margins), *intraplate* (earthquakes far removed from plate margins), and regions of active tectonic *extension* (Halldorsson, 2004; Halldorsson and Papageorgiou, 2005).

In this study, we adopt the calibrated SBM, in conjunction with the stochastic modeling approach, for the synthesis of the incoherent (high-frequency) component of earthquake strong ground motions. The parameters of the SBM and the corresponding seismological models, along with the procedure of strong ground motion simulation, are given by Halldorsson (2004). A general overview of the above is presented in this section, but for more information the reader is referred to Halldorsson (2004).

2.1 Seismological Model

A seismological model estimates, in terms of spectral scaling, the seismic motion at a site as a function of source strength, anelastic and geometric attenuation of seismic waves due to propagation path effects between the source and the site, and wave amplification due to site effects. The general form of a seismological model can be expressed in terms of the Fourier amplitude spectrum (A_s) of the ground acceleration as follows:

$$A_s = E(M_o, f) \cdot P(r, f) \cdot G(f) \cdot I(f) \tag{2-1}$$

where f is frequency (Hz) and:

$E(M_o, f)$ = source model
$P(r, f)$ = propagation path diminution function
$G(f)$ = site amplification function
$I(f)$ = filter used to shape the spectrum according to the type of ground motion (e.g., accelerations, spectral response, etc.) of interest.

2.1.1 Source Model

A source model, or source spectrum, is the model describing the spectrum of the elastic waves radiated by the source before they have been modified by the propagation path and site effects. The reliability of ground motion estimates depends critically on the assumed source spectra in the seismological model. The source model in (2-1) can be written as follows:

$$E(M_o, f) = c \cdot S(M_o, f) \cdot D(f, f_{\max}) \tag{2-2}$$

where:

$S(M_o, f)$ = the spectrum representing the average far-field S-wave radiation of seismic waves from the source (the source displacement spectrum)
$D(f, f_{msx})$ = a high-cut filter with a cut-off frequency f_{max}
c = a frequency-independent scaling factor, given by:

$$c = \frac{R_{\theta\phi} \cdot F \cdot V}{4\pi\rho\beta^3} \tag{2-3}$$

where F is the free surface amplification, V represents the partition onto two horizontal components, and ρ and β are the material density and shear wave velocity, respectively, in the vicinity of the source region.

The Specific Barrier Model (SBM) proposed and developed by Papageorgiou and Aki (1983a, 1983b) is adopted herein as a source model, which is discussed in Section 2.2.

2.1.2 Path Attenuation Model

Seismic wave amplitudes attenuate with increasing travel distance (r) through the earth. This path attenuation is represented by the function:

$$P(r,f) = D_g(r) \cdot D_Q(r,f) \tag{2-4}$$

where:

$D_g(r)$ = the geometric attenuation function

$D_Q(r,f)$ = the anelastic attenuation function, given by:

$$D_Q(r,f) = e^{-\pi f r / Q_s \beta} \tag{2-5}$$

where:

f = frequency

r = source-site distance

Q_s = the total quality factor of S waves

β = shear wave velocity of the medium

2.1.3 Site Conditions

Local site conditions affect the spectral characteristics of seismic waves. The site factor $G(f)$ incorporated into the seismological model accounts for the crustal amplification of waves as they travel upward through the earth as well as the (possible) nonlinear soil amplification due to soft site conditions. The NEHRP-UBC site classes are used as the predictor variables for site response, represented by various frequency dependent amplification (see e.g., Boore and Joyner, 1997; Halldorsson, 2004).

2.1.4 Duration of Motion

The duration of strong ground motion increases with earthquake magnitude and epicentral distance. The total duration of motion (T_d) is given by:

$$T_d = T_s + T_p \tag{2-6}$$

where:

T_s = the source duration

T_p = the duration from propagation path effect

= $0.05r$ (r is the source-site distance in km)

The source duration based on the Specific Barrier Model is given in Section 2.2.

2.1.5 Seismogram Envelopes

Realizations of stationary acceleration time histories having the spectral content and amplitude as specified by the seismological model and the above duration are generated at this point. The accelerations are further amplitude modulated using the temporal modulating function $A(t)$, adopted by Boore (1983):

$$A(t) = at^b e^{-dt} H(t) \tag{2-7}$$

$$b = \frac{-\varepsilon \ln \eta}{1+\varepsilon(\ln \varepsilon - 1)} \tag{2-8}$$

$$d = \frac{b}{\varepsilon T_w} \tag{2-9}$$

$$a = \left[\frac{(2d)^{2b+1}}{\Gamma(2b+1)} \right]^{1/2} \tag{2-10}$$

where:

$H(t)$ = the Heaviside function
a, b, d = the shape parameters
T_w = duration of motion
Γ = the gamma function
η = 0.05
ε = 0.2

2.2 Specific Barrier Model

The Specific Barrier Model (SBM) proposed and developed by Papageorgiou and Aki (1983a, 1983b) is adopted herein as the earthquake source model. The SBM can be applied both in the "near-fault" and the "far-field" regions. The model is based on the concept that strong ground motion is the result of a cumulative contribution of localized cracks distributed on the fault plane which rupture randomly and independently.

In the model, the fault surface is visualized to be composed of an aggregate of circular cracks (or *sub-events*) of equal radius (ρ_o), filling up a rectangular fault plane of length L and width W. The SBM can be described by five parameters: a crack radius (ρ_o), a local stress drop ($\Delta\sigma_L$), a length of a fault plane (L), a width of a fault plane (W), and a rupture velocity (V). Figure 2-1 shows the characteristics of the fault plane in the SBM.

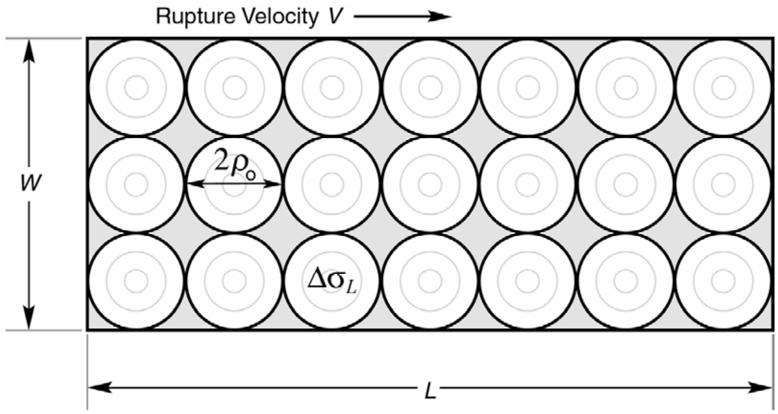


Figure 2-1 Specific Barrier Model: Fault Plane (Papageorgiou and Aki, 1983a, 1983b)

The shaded area represents barriers between the identical circular cracks and the circles within each crack denote the rupture front at successive time intervals. As a fault rupture takes place, the rupture front sweeps the fault plane with a velocity V. A local stress drop $\Delta\sigma_L$ occurs in each crack starting from its center and spreads radially with constant velocity. The ruptures of the individual cracks are assumed to occur independently. The slip stops when the crack radius reaches the size of ρ_o.

2.2.1 Far-field Source Spectrum

The radiation of elastic waves emitted from each sub-event as it breaks is based on a physical description of source processes using kinematic dislocation theory. Papageorgiou and Aki (1983a) derived the far-field expression of the source spectrum radiated from such a crack, but for simplicity, the far-field source spectral shape of each sub-event was approximated with an "ω-square" spectrum by Papageorgiou (1988), who also presented an expression for the far-field source spectrum for the *aggregate* sub-event radiation from the SBM, based on the work of Joyner and Boore (1986). Based on observed deviation from self-similar scaling of high-frequency spectral levels of strong ground motion, Halldorsson and Papageorgiou (2005) modified the expression by introducing a high-frequency source complexity factor, ζ into the expression for the far-field acceleration source spectrum of the SBM:

$$S(M_o, f) = \sqrt{N\left[1+(N-1)\left(\frac{\sin(\pi f T)}{\pi f T}\right)^2\right]}(2\pi f)^2 \tilde{\dot{M}}_{oi}(f) \qquad (2\text{-}11)$$

$$\tilde{\dot{M}}_{oi}(f) = \frac{M_{oi}}{1+(f/f_2)^2} \qquad (2\text{-}12)$$

$$M_{oi} = \frac{16}{7}\Delta\sigma_L \cdot \rho_o^3 \qquad (2\text{-}13)$$

$$f_2 = \frac{C_s \beta}{2\pi\rho_o} \qquad (2\text{-}14)$$

in which:
N = a number of sub-events on the fault (see Figure 2-1)
C_s = a model dependent constant
$\Delta\sigma_L$ = local stress drop

The high-frequency source complexity factor is of the form:

$$\log\varsigma = 2s_m\left(M_w - M_c\right) \tag{2-15}$$

where s_m = -0.12, M_c = 6.35 (Halldorsson and Papageorgiou, 2005) and

$$M_w = \frac{2}{3}\log M_o - 10.7 \tag{2-16}$$

is the moment magnitude of an earthquake of seismic moment M_o in dyne-cm (Hanks and Kanamori, 1979)

2.2.2 Source Duration

The source duration, T_s, of the SBM can be calculated using, e.g.,

$$T_s = \frac{\pi}{2}\left(\frac{7}{16}\cdot\frac{M_o}{\Delta\sigma_G}\right)^{1/3} \tag{2-17}$$

where:
$\Delta\sigma_G$ = global stress drop

The word "global" implies that the stress drop is assumed to be uniform over the entire fault plane in the absence of barriers.

2.2.3 Barrier Interval

All sub-events in a specific tectonic regime are assumed to have the same diameter ($2\rho_o$) referred to as the "barrier interval" of the SBM. The barrier interval relates to the moment magnitude (M_w) of the main event through the following equation (Halldorsson, 2004):

$$\log(2\rho_o) = -1.364 + \frac{2}{3}\log\Delta\sigma_G - \log\Delta\sigma_L + 0.5M_w \tag{2-18}$$

Table 2-1 summarizes the parameters used in the latest calibration of the SBM carried out by Halldorsson (2004) for each tectonic regime, i.e., interplate (e.g., California, Turkey), extensional regime (e.g., the Basin and Range Province, U.S.; Greece), and intra-plate regimes (e.g., Eastern North America).

Table 2-1 Summary of the Parameters Used in the Specific Barrier Model (Halldorsson, 2004)

Model Parameters	Tectonic Regimes		
	Interplate	Extensional	Intra-plate
c	$R_{\theta\phi} = 0.55$ $F = 2.0,\ V = 1/\sqrt{2}$ $\rho = 2.8$ g/cm^3 $\beta = 3.5$ km/s	$R_{\theta\phi} = 0.55$ $F = 2.0,\ V = 1/\sqrt{2}$ $\rho = 2.8$ g/cm^3 $\beta = 3.5$ km/s	$R_{\theta\phi} = 0.55$ $F = 2.0,\ V = 1/\sqrt{2}$ $\rho = 2.8$ g/cm^3 $\beta = 3.8$ km/s
$D_g(r)$	r^{-1} $r \le 30$ km $(30r)^{-0.5}$ $r > 30$ km	r^{-1} $r \le 30$ km $(30r)^{-0.5}$ $r > 30$ km	$1/r$ $r \le 70$ km $1/70$ $70 < r \le 130$ km $1/[70(130/r)^{0.5}]$ $r > 130$ km
Q	$Q_s(f) = 153 f^{0.88}$	$Q_s(f) = 143 f^{0.84}$	$Q_s(f) = 680 f^{0.36}$
Site amplification	Rock: $\overline{V}_{30} = 760$ m/s Soil: Nonlinear	Rock: $\overline{V}_{30} = 940$ m/s Soil: Nonlinear	-
$\Delta\sigma_G$ (bar)	30	30	60
$\Delta\sigma_L$ (bar)	161	114	180

This discussion serves as a brief overview of the governing equations of the stochastic modeling approach and the specific barrier model. For more details, the reader is referred to Boore (2003) and Halldorsson (2004), respectively. The latter reference includes a detailed description of both the stochastic modeling approach and the SBM, its calibrations, the selection procedure of scenario earthquake events on the basis of disaggregated seismic hazard for a site, and how the corresponding strong motions are synthesized. Note that the SBM code, namely SGMSv5, with the most recent calibration (Halldorsson, 2004) is used in this study. The SGMSv5 coded in FORTRAN 90 and the user's manual is available at http://civil.eng.buffalo.edu/EngSeisLab/.

SECTION 3
SIMULATION OF WEST COAST HORIZONTAL GROUND MOTIONS

This section presents the procedure for simulation of the strong ground motions representative of an assumed hospital site located on the west coast of the United States. This includes high-frequency ground motion simulation using the methodology mentioned in Section 2, in addition to low-frequency velocity pulse simulation for near-fault sites (Mavroeidis and Papageorgiou, 2003). The general procedures are explained in more detail in Halldorsson (2004), and the results in this section show a specific case for the selected west coast site.

3.1 Fault-Site Model

For the U.S. west coast location, the site is considered to be in the "near-fault" region. In this case the "far-field" assumption breaks down, requiring the simulation of time histories for each individual sub-event (or crack, see Section 2) of the SBM, rather than using the "aggregate" far-field source spectrum of the SBM.

To simulate the strong ground motions for the near-field site, information on the configuration of the seismic source must be specified, e.g., fault-site orientation, location of the hypocenter, location of the fault plane, size and orientation of the fault plane, etc.

3.1.1 Assumptions

Figure 3-1 and 3-2 illustrate the assumed plan and elevation views of the fault-site model, respectively.

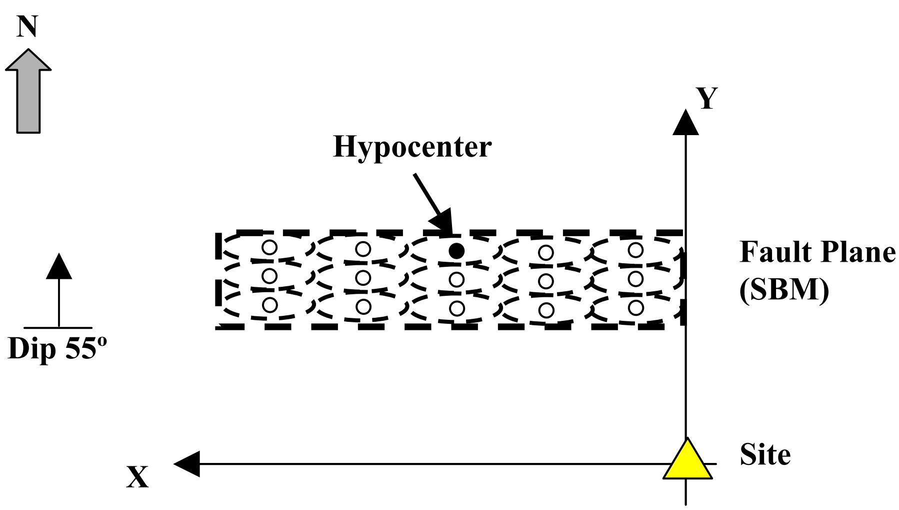


Figure 3-1 Fault-Site Model: Plan View

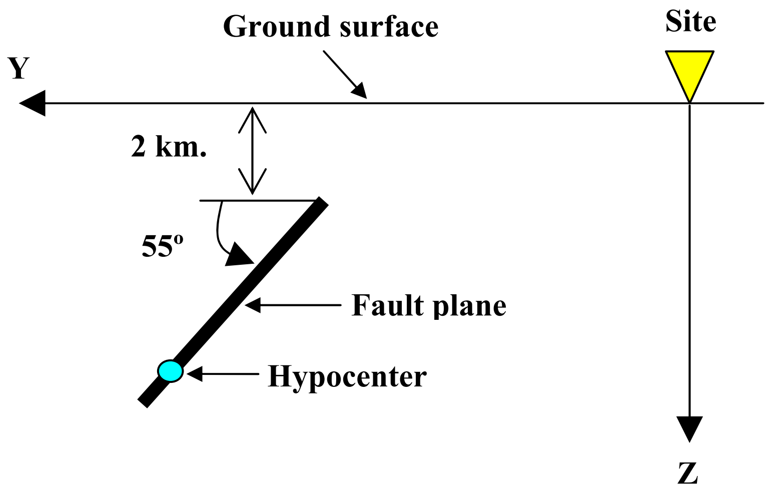


Figure 3-2 Fault-Site Model: Elevation View

Several assumptions related to the fault-site model were made as follows:

- A fault configuration similar to the Santa Susana fault in Northridge, California is selected as the prototype configuration. The fault lies in the east-west direction with a dip angle of 55º to the north.
- The top edge of the fault plane in the SBM is assumed to be located at 2-km below the ground surface.
- A total of 15 sub-events (circular cracks) is selected. The number of circular cracks along the length of the fault is 5. The number of circular cracks along the width of the fault is 3. With this configuration, the ratio of the number of sub-events along the length and width of the fault plane is approximately equal to 2, which is the same as used in the latest calibration of the SBM (Halldorsson, 2004) for interplate earthquakes (e.g., California).
- Shear-wave and rupture velocities are assumed to be 3.3 and 2.6 km/sec, respectively.

All sub-events of the SBM have the same diameter of $2\rho_o$, referred to as the barrier interval of the SBM. The barrier interval for interplate earthquakes relates to the moment magnitude of the event through the following simplified equation (refer to Equation (2-16) and Table 2-1):

$$\log(2\rho_o) = -2.586 + 0.5M_w \tag{3-1}$$

where:
ρ_o = radius of each individual sub-event (crack) of the SBM (in km.)
M_w = moment magnitude of the event

With the size of each circular crack, the source-site distance and the fault orientation can be used to obtain fault-site geometry, which is needed in the simulation procedure.

3.2 Near-Fault Pulse Simulation

Time histories generated by the SBM cannot accurately replicate the impulsive characteristic of the near-fault strong ground motions. Recently, Mavroeidis and Papageorgiou (2003) proposed a simple, yet effective, analytical model for the representation of the near-fault strong ground motions. The model, which has been calibrated using a large number of actual near-fault records, can adequately describe the impulsive character of the near-fault ground motions both qualitatively and quantitatively. Mavroeidis and Papageorgiou (2003) also proposed a simplified methodology (to be described in Section 3.4) for the generation of realistic, broadband, near-fault accelerograms adequate for engineering applications.

The analytical model proposed by Mavroeidis and Papageorgiou (2003) is adopted herein for the simulation of the near-fault ground motion pulses. The pulse duration (or period), the pulse amplitude, and the number and phase of half cycles are the key input parameters of the analytical model. The acceleration time history of the near-fault pulse is expressed by the following equation:

when $t_0 - \frac{\gamma}{2f_p} \le t \le t_0 + \frac{\gamma}{2f_p}$ with $\gamma > 1$

$$a(t) = -\frac{A\pi f_p}{\gamma}\left[\sin\left(\frac{2\pi f_p}{\gamma}(t-t_0)\right)\cos\left(2\pi f_p(t-t_0)+\nu\right)+\gamma\sin\left(2\pi f_p(t-t_0)+\nu\right)\left(1+\cos\left(\frac{2\pi f_p}{\gamma}(t-t_0)\right)\right)\right]$$

otherwise; $a(t) = 0$ (3-2)

where:
$a(t)$ = near-fault pulse acceleration (cm/sec^2)
A = pulse velocity amplitude (cm/sec)
γ = oscillatory character (zero-crossings)
ν = phase angle
f_p = prevailing frequency (H_z)
t_o = time shift (sec)

Table 3-1 summarizes "average" values for parameters γ and ν based on information provided by Mavroeidis and Papageorgiou (2003) for strong motion records from the 1994 Northridge, California, earthquake. These values are used for all simulated near-fault pulses.

Table 3-1 Parameters γ and ν for Near-Fault Pulse Simulation

Parameter	Direction of Horizontal Ground Motion	
	Fault-Normal	Fault-Parallel
γ	2.0	1.005
ν	65º	0º

A parameter t_o can be determined from the fault-site geometry (source-to-site distance). The prevailing frequency (f_p) can be calculated using the equation:

$$\log f_p = 2.9 - 0.5M_w \tag{3-3}$$

To determine the amplitude of the pulse velocity (A) for the "fault-normal" direction, rather than using a constant "average" value, an attenuation relationship as shown below is utilized:

$$A_n = \frac{a}{\sqrt{R_h^2 + b}} \quad \text{(fault-normal direction)} \tag{3-4}$$

$$A_p = 0.5A_n \quad \text{(fault-parallel direction)} \tag{3-5}$$

where:
A_n = pulse velocity amplitude in a "fault-normal" direction (cm/sec)
A_p = pulse velocity amplitude in a "fault-parallel" direction (cm/sec)
R_h = horizontal distance (km)
a = 820
b = 8.0

Figure 3-3 compares the recorded and predicted pulse velocity amplitudes.

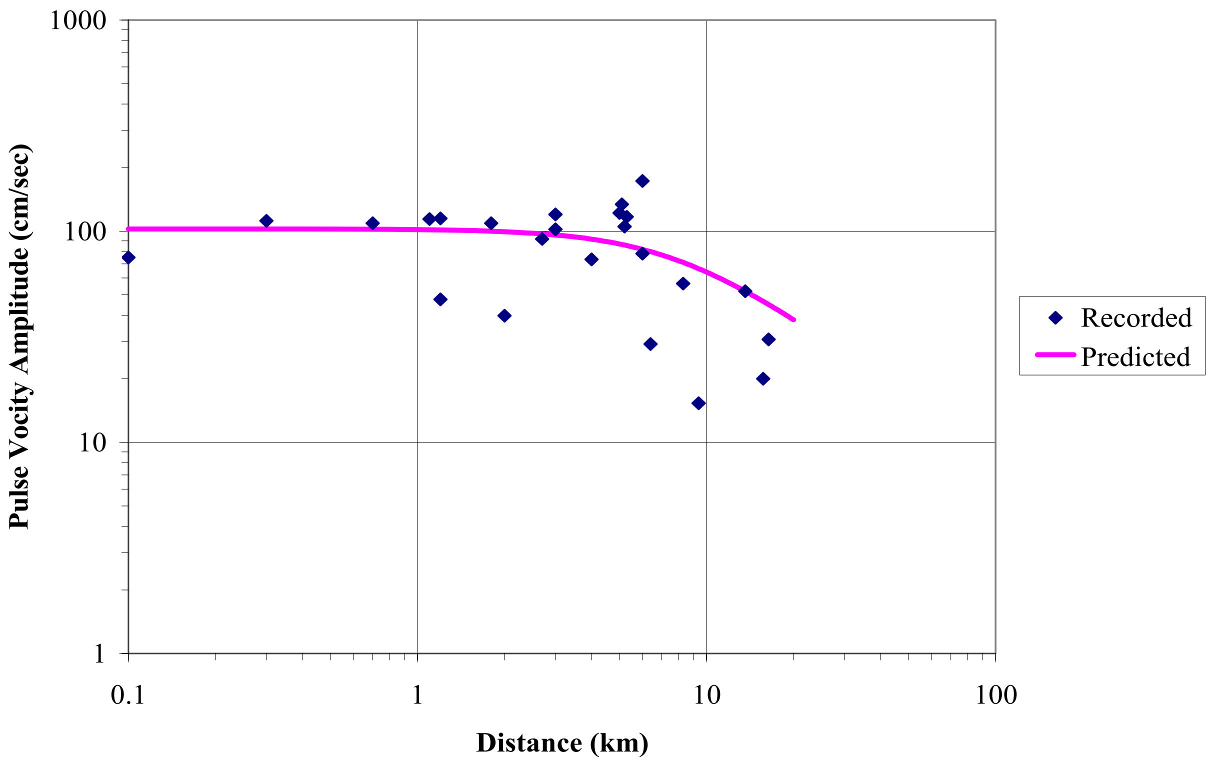
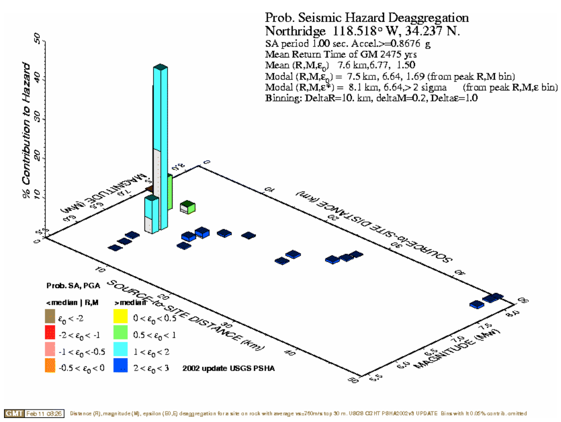


Figure 3-3 Variation of Pulse Velocity Amplitude with Distance: Recorded VS Predicted

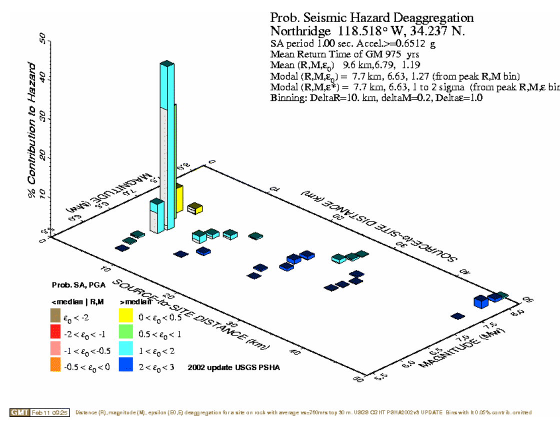
Note that the constants *a* and *b* are obtained from minimizing the square root sum square of the errors between the predicted amplitudes and the values available in the paper by Mavroeidis and Papageorgiou (2003).

3.3 Seismic Hazard Disaggregation and Scenario Earthquakes

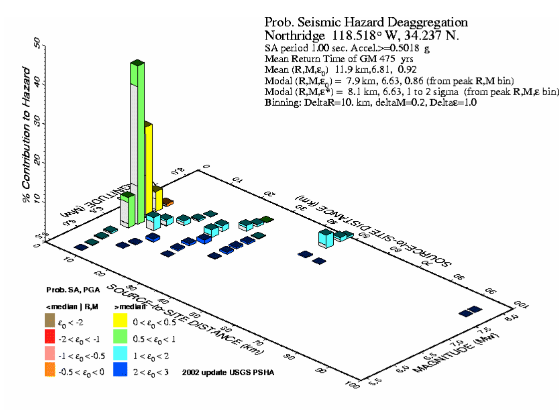
The simulated ground motions are scaled to match (best fit) the uniform hazard spectra provided by the U.S. Geological Survey (USGS). Four different hazard levels are considered: 2%, 5%, 10%, and 20% probabilities of exceedance in 50 years. The disaggregation data from the year 2002 are used for scaling. From these disaggregation charts, the scenario earthquake events (magnitude-distance pairs) required for simulating the ground motions can be obtained. Figure 3-4 depicts the USGS seismic hazard disaggregation (at a period of 1.0 sec corresponding approximately to the fundamental period of the MCEER West Coast Demonstration Hospital) for Northridge, California, with different hazard levels. Figure 3-5 illustrates the USGS uniform hazard spectra.



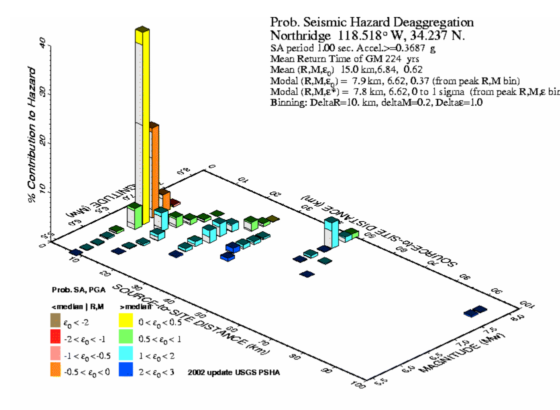
2% Probability of Exceedance in 50 Yrs.



5% Probability of Exceedance in 50 Yrs.



10% Probability of Exceedance in 50 Yrs.



20% Probability of Exceedance in 50 Yrs.

Figure 3-4 Seismic Hazard Disaggregation: Northridge, CA. (USGS, 2002)

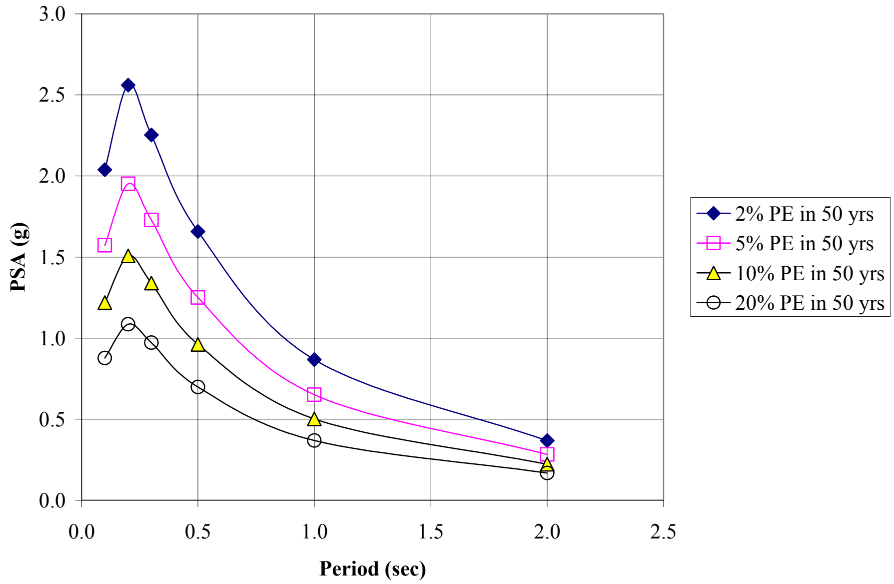


Figure 3-5 USGS Uniform Hazard Spectra: Northridge, CA.

To select the scenarios for simulations, the magnitude-distance pairs from the USGS uniform hazard spectra are considered. The total number of earthquakes in each bin (each probability of exceedance) is 25, i.e., 25 fault-normal and 25 fault-parallel components. The percentage of contribution to the hazard at the site for each event equals 4%; hence any scenarios having a hazard contribution of less than 4% are neglected. The total numbers of earthquakes in each scenario are proportional to their corresponding percentages of contribution to the hazard. Tables 3-2 to 3-5 present the selected scenarios and total numbers of earthquake events in each scenario for each seismic hazard considered.

Table 3-2 Selected Scenarios: 2% Probability of Exceedance in 50 Years

Scenario No.	M_w	R (km)	Contribution to the hazard (%)	Proportion	Numbers of events
1	6.6	7.5	40.7	0.45	11
2	6.8	5.7	33.4	0.37	10
3	7.1	4.6	8.5	0.09	2
4	4.6	7.5	8.4	0.09	2
		Total	91.0	1.00	25

Table 3-3 Selected Scenarios: 5% Probability of Exceedance in 50 Years

Scenario No.	M_w	R (km)	Contribution to the hazard (%)	Proportion	Numbers of events
1	6.6	7.7	41.8	0.49	12
2	6.8	6.3	29.0	0.34	9
3	6.5	7.5	7.4	0.09	2
4	7.1	5.5	6.3	0.07	2
		Total	84.5	1.00	25

Table 3-4 Selected Scenarios: 10% Probability of Exceedance in 50 Years

Scenario No.	M_w	R (km)	Contribution to the hazard (%)	Proportion	Numbers of events
1	6.6	7.9	40.5	0.53	12
2	6.9	6.6	23.0	0.30	8
3	6.5	7.5	7.7	0.10	3
4	7.1	6.4	5.1	0.07	2
		Total	76.3	1.00	25

Table 3-5 Selected Scenarios: 20% Probability of Exceedance in 50 Years

Scenario No.	M_w	R (km)	Contribution to the hazard (%)	Proportion	Numbers of events
1	6.6	7.9	39.3	0.59	14
2	6.9	7.0	18.3	0.27	7
3	7.8	47.2	5.2	0.08	2
4	6.5	8.2	4.3	0.06	2
		Total	67.1	1.00	25

3.4 Simulation Procedure

A simple methodology to simulate near-field accelerograms proposed by Mavroeidis and Papageorgiou (2003) is summarized here. The method exploits the simple analytical model described in Section 3-2 to generate a low-frequency component (a near-fault pulse) that is superimposed to a high-frequency component generated using the stochastic modeling approach and the SBM. The procedure of Mavroeidis and Papageorgiou (2003) is as follows:

Step 1: Generate the near-fault pulse

For each selected scenario (magnitude and distance), calculate the prevailing frequency (f_p) using Equation (3-3). For selected values of the required parameters (A, γ and ν), generate the pulse for the fault-normal and the fault-parallel components using Equation (3-2).

Step 2: Generate a time history from the Specific Barrier Model

For the selected fault-site geometry, generate a time history by summing all 15 sub-events of the SBM with the appropriate time lags which can be determined from source-site distance of each sub-event (each circular crack). Note that the result from each run of the computer code SGMSv5 (refer to Section 2) has three accelerograms. The time histories with the highest and the second highest peak spectra are chosen to simulate the earthquakes in the fault-normal and fault-parallel directions, respectively.

Step 3: Calculate the Fourier amplitude spectra

Calculate the Fourier amplitude spectra of the time histories generated in Step 1 and 2.

Step 4: Calculate the differential Fourier amplitude spectra

Subtract the Fourier amplitude spectrum of the time history in Step 1 from the Fourier amplitude spectrum of the time history created in Step 2. This step can be considered as removing the low-frequency energy from the generated accelerogram.

Step 5: Generate the high-frequency component

Generate a synthetic acceleration-time history that satisfies the following conditions:

(1) Its Fourier amplitude spectrum is equal to the difference of the Fourier amplitude spectra calculated in Step 4.
(2) Its phase coincides with the phase of the Fourier transform of the time history generated in Step 2.

Step 6: Scale the high-frequency components

For each ensemble (each hazard level), the "mean" response spectra of all high-frequency, fault-normal components simulated from Step 5 are scaled to match on average the USGS uniform hazard spectra at discrete periods of 0.1, 0.2, 0.3, 0.5, and 1.0 seconds. By minimizing the square root sum square of the errors, the scaling factors giving the best fit can be obtained. The same scaling factors are applied to the fault-parallel components.

Step 7: Generate the near-fault ground motion

Superimpose the pulse (Step 1) to the scaled high-frequency component (Step 6) to get the near-fault accelerogram. The near-fault pulse is shifted in time so that the peak of its envelope coincides with the time that the rupture front passes in front of the site.

Note that for each scenario (magnitude and distance pair), the pulse combining with those high-frequency components is the same. By varying the seed numbers, the high-frequency time histories can be randomly generated, which results in different final near-fault time histories.

3.5 Resulting Simulated Ground Motions

As an example, the simulation of a 6.6 M_w, 7.5 km scenario for a hazard level of 2% probability of exceedance in 50 years, is demonstrated in this section. The time histories from 15 sub-events of the SBM are shown in Figure 3-6. The time lag of each sub-event is determined from the source-site distance of each sub-event with the shear-wave and the rupture velocities.

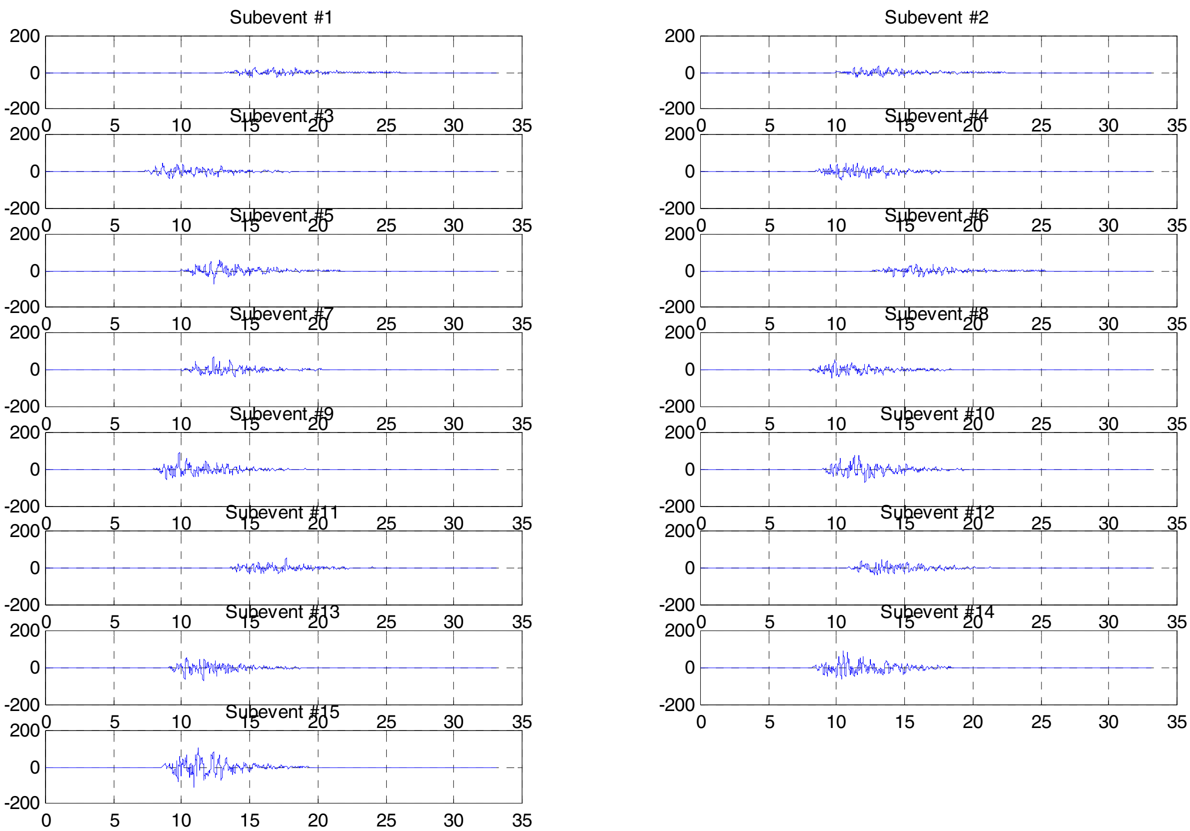


Figure 3-6 Time Histories from 15 Sub-events: 2% Probability of Exceedance in 50 Years, Scenario 1, Event 1 (6.6 M_w, 7.5 km)

Table 3-6 summarizes the scaling factors for each hazard level. Figure 3-7 compares the unscaled and scaled "mean" response spectra with the USGS uniform hazard spectrum. The pulse, the scaled high-frequency component, and the final near-fault accelerograms (fault-normal component) are presented in Figure 3-8.

Table 3-6 Scaling Factors for each Hazard Level

Probability of Exceedance in 50 Years	Scaling Factor
2 %	4.45
5 %	3.47
10 %	2.62
20 %	2.03

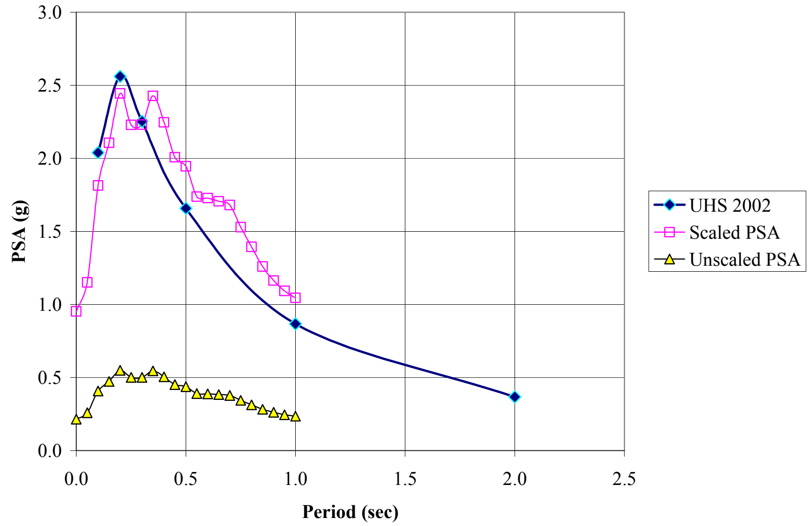
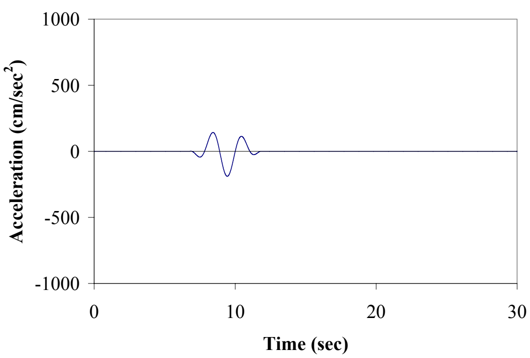
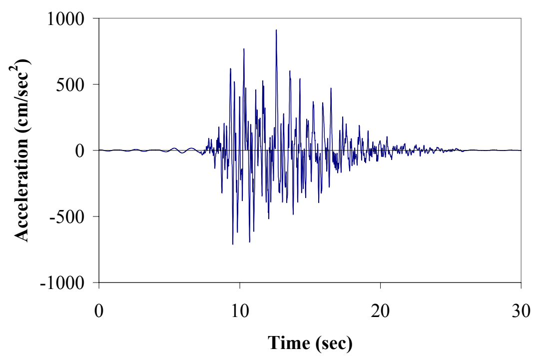


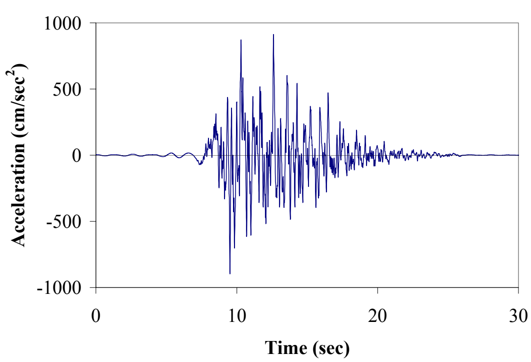
Figure 3-7 Scaling of Response Spectra



Near-Fault Pulse



Scaled High-Frequency Component



Final Near-Fault Ground Motion

Figure 3-8 Simulation of Near-Fault Ground Motion: 2% Probability of Exceedance in 50 Years (6.6 M_w, 7.5 km)

By changing the pulse parameters (A, γ, and ν) as described previously, the fault-parallel component can be generated. Figure 3-9 depicts the accelerogram of the fault-parallel component. Figure 3-10 compares the response spectra of the simulated near-fault ground motions. Figures 3-11 to 3-14 compare the statistical response spectra of all simulated near-fault ground motions with the USGS uniform hazard spectrum. The time histories and their corresponding response spectra of each individual event are summarized in Appendix A.

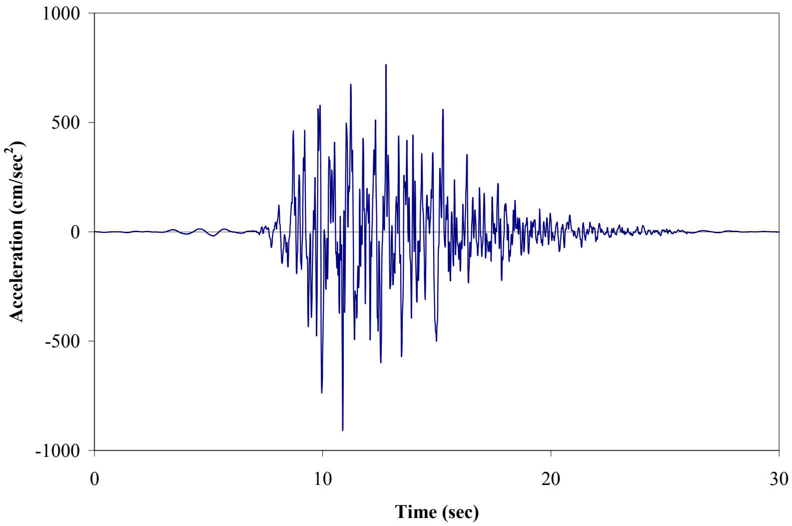


Figure 3-9 Acceleration-Time History: Fault-Parallel, 2% Probability of Exceedance in 50 Years (6.6 M_w, 7.5 km)

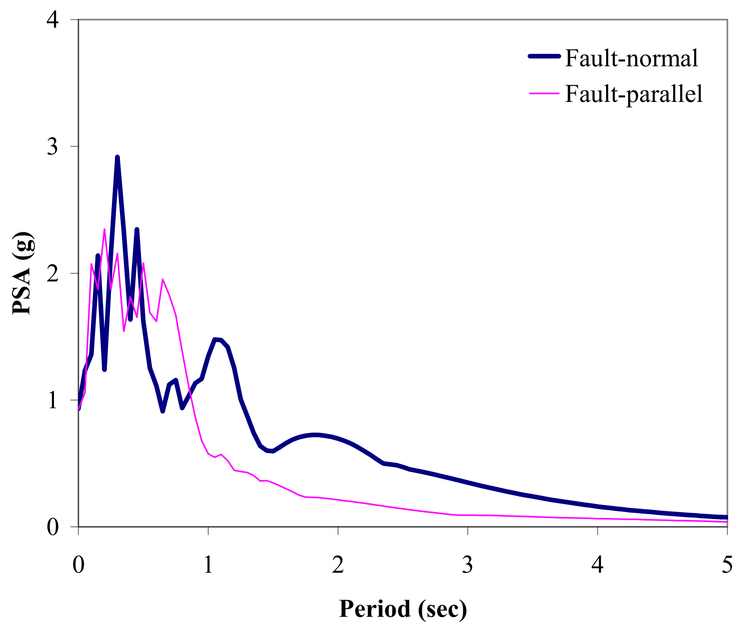
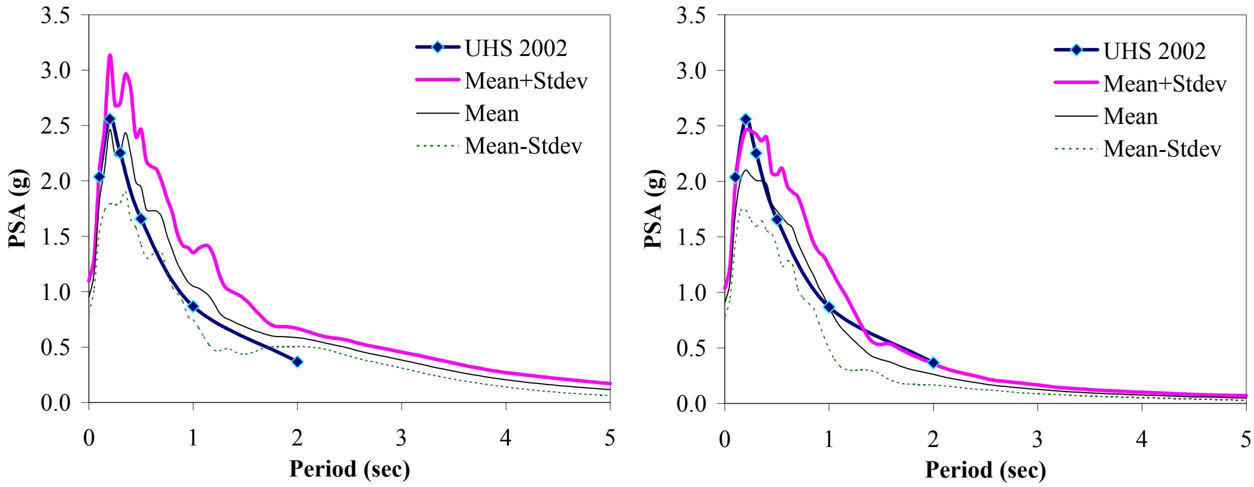


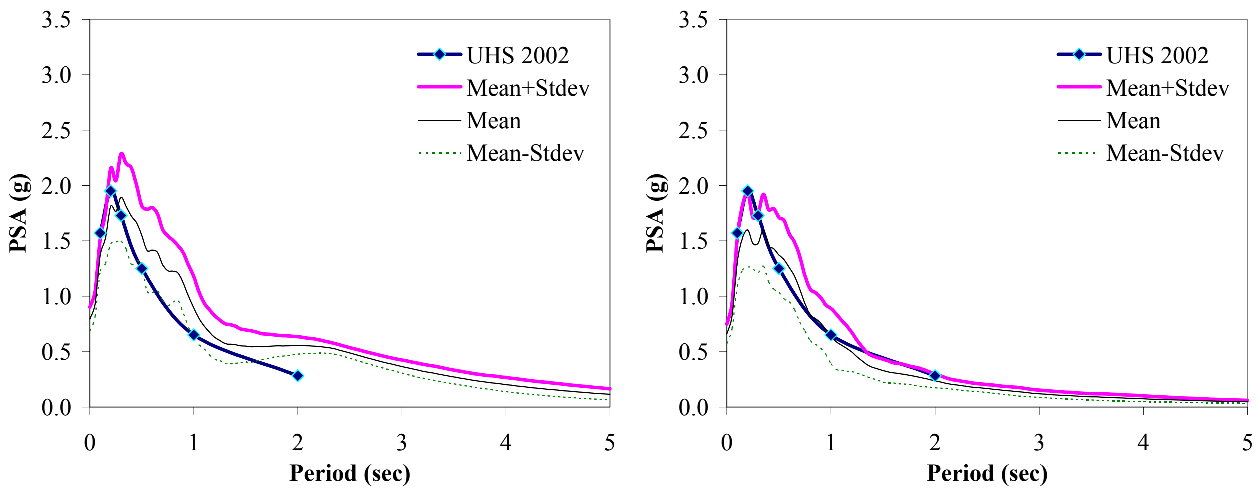
Figure 3-10 Response Spectra of Simulated Earthquakes: 2% Probability of Exceedance in 50 Years (6.6 M_w, 7.5 km)



Fault-Normal Component

Fault-Parallel Component

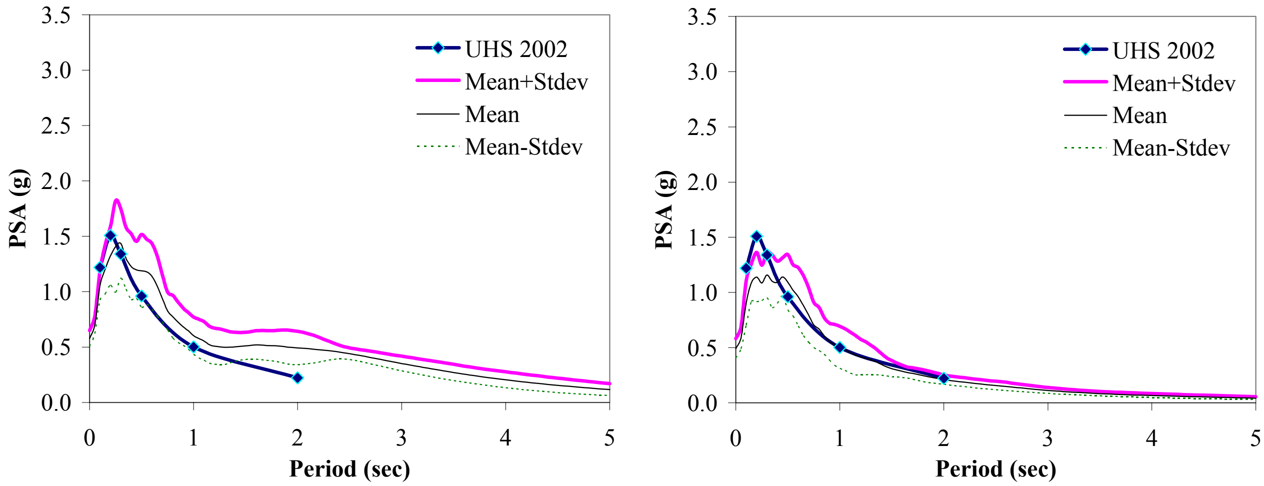
Figure 3-11 Statistical Response Spectra VS Uniform Hazard Spectrum: 2% Probability of Exceedance in 50 Years



Fault-Normal Component

Fault-Parallel Component

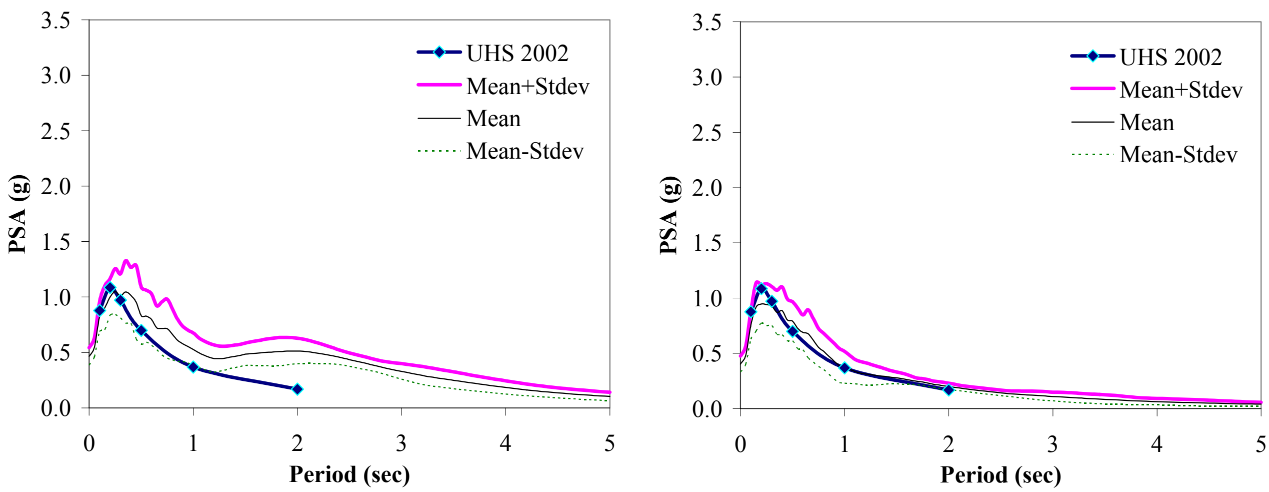
Figure 3-12 Statistical Response Spectra VS Uniform Hazard Spectrum: 5% Probability of Exceedance in 50 Years



Fault-Normal Component

Fault-Parallel Component

Figure 3-13 Statistical Response Spectra VS Uniform Hazard Spectrum: 10% Probability of Exceedance in 50 Years



Fault-Normal Component

Fault-Parallel Component

Figure 3-14 Statistical Response Spectra VS Uniform Hazard Spectrum: 20% Probability of Exceedance in 50 Years

SECTION 4
SIMULATION OF EAST COAST HORIZONTAL GROUND MOTIONS

This section presents the procedure and the results of the simulated ground motions representative of a hypothetical hospital site on the east coast of the United States. Two ensembles of ground motions are simulated, i.e., one for experimental purposes and another for analytical studies.

4.1 Fault-Site Model

In contrast to the US west coast, Eastern North America (ENA) site conditions are considered to be "far-field." Due to the large source-site distance relative to the size of the fault, the source can be considered as a "point-source." Therefore, the entire event can be simulated without generating and summing up the sub-events, which were required for simulating the near-field ground motions, as described in Section 3. The far-field source spectrum of the Specific Barrier Model (SBM) described in Section 2 is used for all simulations. Only a few parameters are required for the simulations using the SGMSv5 code, i.e., tectonic regime, moment magnitude, source-site distance, soil condition, and seed number. Figure 4-1 shows the fault-site model considered for ENA sites.

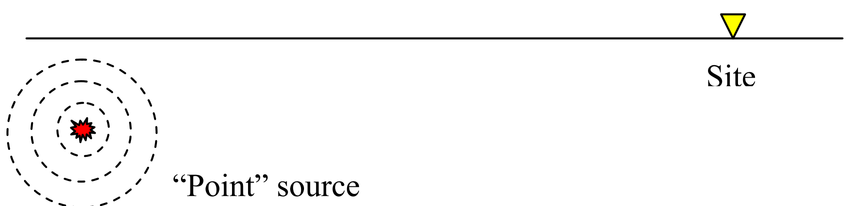


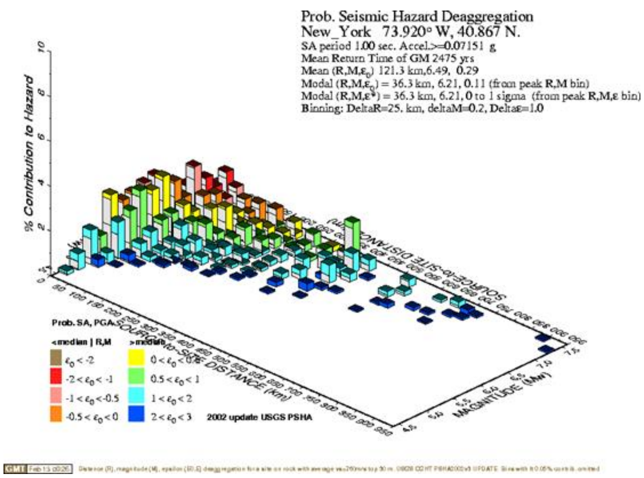
Figure 4-1 Fault-Site Model for Earthquakes in ENA

4.2 Seismic Hazard Disaggregation and Earthquake Scenarios

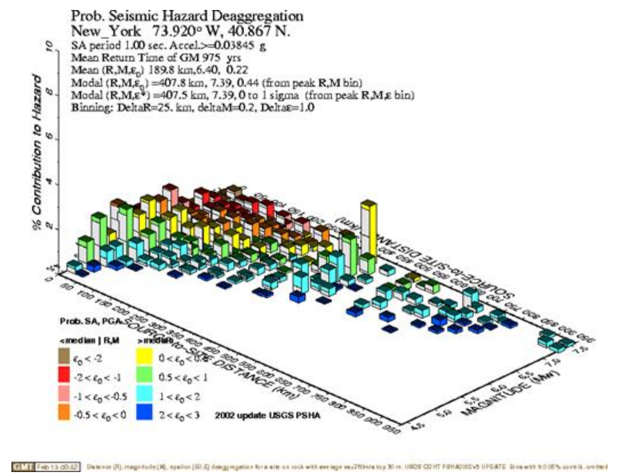
Unlike the west coast, a large number of magnitude-distance scenarios contribute to the hazard at an ENA site. Hence, two ensembles of earthquakes are simulated. The first "short" ensemble contains 50 ground motions for each hazard level (50 fault-normal and 50 fault-parallel ground motions) with a minimum percentage of contribution to the hazard of 2% for each event. The summation of the percentages of hazard contribution for this group is small due to the fact that only a limited number of scenarios are included. This ensemble may be suitable for experimental programs.

The second "long" ensemble contains 100 ground motions for each hazard level (100 fault-normal and 100 fault-parallel accelerograms). Each event has an average percentage of contribution to the hazard of 1%. The total percentage of contribution to the hazard for this group is higher than 50%. The simulated ground motions from this ensemble are more appropriate for analytical studies.

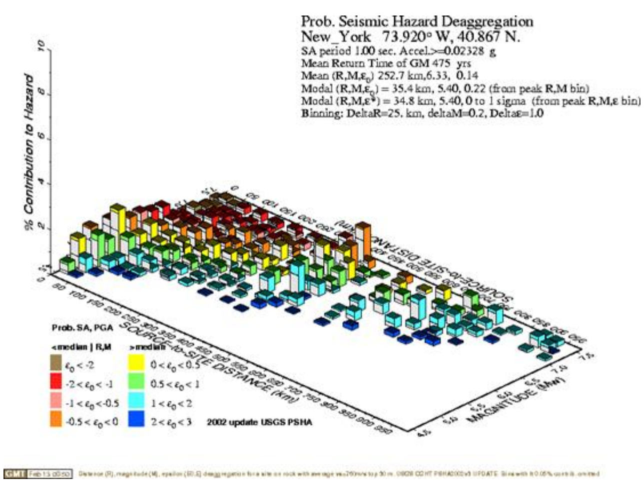
Similar to the west coast study, four different hazard levels are considered, i.e., 2%, 5%, 10%, and 20% probabilities of exceedance in 50 years for a site in New York. Figure 4-2 presents the USGS seismic hazard disaggregation at a period of 1 sec for an hypothetical hospital site in New York City.



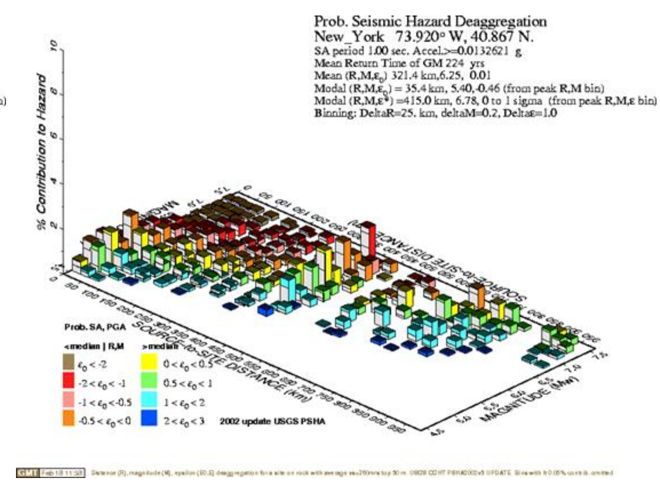
2% Probability of Exceedance in 50 Yrs.



5% Probability of Exceedance in 50 Yrs.



10% Probability of Exceedance in 50 Yrs.



20% Probability of Exceedance in 50 Yrs.

Figure 4-2 Seismic Hazard Disaggregation: New York (USGS, 2002)

As described above, the short ensemble contains 50 ground motions for each hazard level. Hence, any scenarios with a percentage of contribution to the hazard at the site less than 2% is neglected. Similarly, all scenarios with hazard contribution of less than 1% are neglected for the long ensemble of ground motions. Tables 4-1 to 4-4 and Tables 4-5 to 4-8 show the selected earthquake scenarios and the total numbers of earthquake events in each scenario for the short and the long ensembles, respectively.

Table 4-1 Selected Scenarios: 2% Probability of Exceedance in 50 Yrs. (Short Ensemble, 50 events/bin)

Scenario No.	M_w	R (km)	Contr (%)	Proportn	No. of Events	Scenario No.	M_w	R (km)	Contr (%)	Proportn	No. of Events
1	6.2	36.3	2.8	0.07	4	10	5.6	13.6	2.2	0.06	3
2	5.4	13.2	2.7	0.07	4	11	5.6	33.6	1.9	0.05	2
3	6.2	15.6	2.7	0.07	4	12	6.4	15.2	1.9	0.05	2
4	5.8	33.7	2.6	0.07	4	13	7.4	385.0	1.8	0.05	2
5	6.8	36.2	2.5	0.07	3	14	7.0	35.0	1.8	0.05	2
6	6.0	15.5	2.5	0.07	3	15	7.4	35.1	1.6	0.04	2
7	6.0	35.9	2.4	0.06	3	16	5.4	32.5	1.6	0.04	2
8	5.8	13.9	2.3	0.06	3	17	6.8	14.4	1.6	0.04	2
9	6.4	36.2	2.3	0.06	3	18	5.0	11.9	1.5	0.04	2
								Total	38.6	1.00	50

Table 4-2 Selected Scenarios: 5% Probability of Exceedance in 50 Yrs. (Short Ensemble, 50 events/bin)

Scenario No.	M_w	R (km)	Contr (%)	Proportn	No. of Events	Scenario No.	M_w	R (km)	Contr (%)	Proportn	No. of Events
1	7.4	407.8	2.7	0.12	6	7	6.0	36.5	1.9	0.09	4
2	5.4	14.6	2.2	0.10	5	8	5.6	16.2	1.7	0.08	4
3	5.4	34.1	2.2	0.10	5	9	5.6	36.4	1.7	0.08	4
4	6.2	35.6	2.1	0.10	5	10	7.0	413.5	1.7	0.08	4
5	5.8	36.2	2.1	0.10	5	11	5.8	15.9	1.6	0.07	3
6	5.0	14.5	2.0	0.09	5			**Total**	21.7	1.00	50

Table 4-3 Selected Scenarios: 10% Probability of Exceedance in 50 Yrs. (Short Ensemble, 50 events/bin)

Scenario No.	M_w	R (km)	Contr (%)	Proportn	No. of Events	Scenario No.	M_w	R (km)	Contr (%)	Proportn	No. of Events
1	5.4	35.4	2.1	0.21	10	4	5.4	15.5	1.6	0.16	8
2	7.4	416.1	1.7	0.17	8	5	5.8	36.9	1.6	0.15	8
3	5.0	13.8	1.6	0.16	8	6	5.6	35.9	1.6	0.15	8
								Total	10.2	1.00	50

Table 4-4 Selected Scenarios: 20% Probability of Exceedance in 50 Yrs. (Short Ensemble, 50 events/bin)

Scenario No.	M_w	R (km)	Contr (%)	Proportn	No. of Events	Scenario No.	M_w	R (km)	Contr (%)	Proportn	No. of Events
1	5.4	35.4	1.9	0.22	11	4	7.4	392.3	1.6	0.18	9
2	6.4	417.6	1.8	0.21	11	5	5.0	35.3	1.5	0.18	9
3	6.8	415.2	1.8	0.21	10			**Total**	8.6	1.00	50

Table 4-5 Selected Scenarios: 2% Probability of Exceedance in 50 Yrs.
(Long Ensemble, 100 events/bin)

Scenario No.	M_w	R (km)	Contr (%)	Proportn	No. of Events	Scenario No.	M_w	R (km)	Contr (%)	Proportn	No. of Events
1	6.2	36.3	2.8	0.03	3	34	5.8	62.4	0.9	0.01	1
2	5.4	13.2	2.7	0.03	3	35	7.4	171.8	0.9	0.01	1
3	6.2	15.6	2.7	0.03	3	36	7.4	11.3	0.9	0.01	1
4	5.8	33.7	2.6	0.03	3	37	6.2	84.7	0.9	0.01	1
5	6.8	36.2	2.5	0.03	3	38	7.4	127.9	0.9	0.01	1
6	6.0	15.5	2.5	0.03	3	39	7.2	413.3	0.9	0.01	1
7	6.0	35.9	2.4	0.03	3	40	7.2	63.7	0.8	0.01	1
8	5.8	13.9	2.3	0.03	3	41	6.4	86.1	0.8	0.01	1
9	6.4	36.2	2.3	0.03	3	42	6.8	177.0	0.8	0.01	1
10	5.6	13.6	2.2	0.03	3	43	7.0	120.4	0.8	0.01	1
11	5.6	33.6	1.9	0.02	2	44	6.8	410.4	0.8	0.01	1
12	6.4	15.2	1.9	0.02	2	45	7.0	87.2	0.8	0.01	1
13	7.4	385.0	1.8	0.02	2	46	7.4	87.2	0.8	0.01	1
14	7.0	35.0	1.8	0.02	2	47	4.8	10.6	0.7	0.01	1
15	7.4	35.1	1.6	0.02	2	48	7.0	173.0	0.7	0.01	1
16	5.4	32.5	1.6	0.02	2	49	7.2	11.8	0.7	0.01	1
17	6.8	14.4	1.6	0.02	2	50	7.4	222.5	0.7	0.01	1
18	5.0	11.9	1.5	0.02	2	51	7.0	367.7	0.6	0.01	1
19	6.6	38.0	1.4	0.02	2	52	6.6	85.8	0.6	0.01	1
20	6.8	61.9	1.4	0.02	2	53	7.2	124.0	0.6	0.01	1
21	6.4	61.3	1.4	0.02	2	54	5.6	61.4	0.6	0.01	1
22	6.6	16.0	1.4	0.02	2	55	7.4	278.6	0.6	0.01	1
23	6.8	123.2	1.3	0.02	2	56	6.2	126.3	0.6	0.01	1
24	6.2	60.2	1.3	0.02	2	57	6.8	222.1	0.6	0.01	1
25	7.0	62.0	1.2	0.02	2	58	6.6	172.2	0.5	0.01	1
26	6.0	62.9	1.2	0.02	1	59	6.8	335.4	0.5	0.01	1
27	7.2	34.8	1.2	0.02	1	60	7.2	337.0	0.5	0.01	1
28	7.4	62.3	1.1	0.01	1	61	7.0	130.9	0.5	0.01	1
29	5.2	12.5	1.1	0.01	1	62	7.4	431.7	0.5	0.01	1
30	7.0	13.3	1.1	0.01	1	63	6.0	119.0	0.5	0.01	1
31	6.8	85.8	1.0	0.01	1	64	7.4	118.4	0.5	0.01	1
32	6.4	122.6	1.0	0.01	1	65	6.6	129.9	0.5	0.01	1
33	6.6	61.6	0.9	0.01	1			**Total**	78.7	1.00	100

Table 4-6 Selected Scenarios: 5% Probability of Exceedance in 50 Yrs. (Long Ensemble, 100 events/bin)

Scenario No.	M_w	R (km)	Contr (%)	Proportn	No. of Events	Scenario No.	M_w	R (km)	Contr (%)	Proportn	No. of Events
1	7.4	407.8	2.7	0.04	4	37	7.0	343.4	0.8	0.01	1
2	5.4	14.6	2.2	0.03	3	38	6.8	121.1	0.8	0.01	1
3	5.4	34.1	2.2	0.03	3	39	6.4	172.4	0.8	0.01	1
4	6.2	35.6	2.1	0.03	3	40	6.6	123.3	0.8	0.01	1
5	5.8	36.2	2.1	0.03	3	41	6.2	87.7	0.8	0.01	1
6	5.0	14.5	2.0	0.03	3	42	6.6	414.8	0.8	0.01	1
7	6.0	36.5	1.9	0.03	3	43	6.2	396.9	0.7	0.01	1
8	5.6	16.2	1.7	0.02	2	44	6.4	120.1	0.7	0.01	1
9	5.6	36.4	1.7	0.02	2	45	7.4	689.1	0.7	0.01	1
10	7.0	413.5	1.7	0.02	2	46	5.2	34.0	0.7	0.01	1
11	5.8	15.9	1.6	0.02	2	47	6.6	63.1	0.7	0.01	1
12	6.2	62.8	1.4	0.02	2	48	7.4	35.5	0.7	0.01	1
13	6.4	37.2	1.3	0.02	2	49	7.2	433.9	0.7	0.01	1
14	5.8	63.2	1.3	0.02	2	50	5.0	34.8	0.7	0.01	1
15	6.8	36.8	1.3	0.02	2	51	7.4	124.6	0.7	0.01	1
16	6.0	63.5	1.3	0.02	2	52	5.8	121.0	0.7	0.01	1
17	6.0	15.8	1.3	0.02	2	53	7.0	61.9	0.7	0.01	1
18	4.8	12.7	1.2	0.02	2	54	6.2	176.2	0.7	0.01	1
19	5.2	14.6	1.1	0.02	2	55	6.8	14.4	0.6	0.01	1
20	6.8	410.1	1.1	0.02	2	56	7.4	278.8	0.6	0.01	1
21	6.2	122.6	1.1	0.02	2	57	6.0	120.2	0.6	0.01	1
22	6.2	14.3	1.0	0.01	1	58	7.4	222.6	0.6	0.01	1
23	6.4	60.3	1.0	0.01	1	59	6.0	89.3	0.6	0.01	1
24	5.6	62.7	1.0	0.01	1	60	7.0	126.6	0.6	0.01	1
25	7.2	387.6	0.9	0.01	1	61	6.8	274.0	0.5	0.01	1
26	6.8	173.8	0.9	0.01	1	62	7.0	222.0	0.5	0.01	1
27	6.8	378.9	0.9	0.01	1	63	7.0	86.7	0.5	0.01	1
28	6.4	16.3	0.9	0.01	1	64	7.2	35.2	0.5	0.01	1
29	6.4	84.9	0.9	0.01	1	65	7.4	171.4	0.5	0.01	1
30	7.4	343.9	0.9	0.01	1	66	6.6	15.2	0.5	0.01	1
31	6.6	37.2	0.9	0.01	1	67	7.4	84.7	0.5	0.01	1
32	6.4	363.9	0.8	0.01	1	68	7.0	179.5	0.5	0.01	1
33	7.0	35.2	0.8	0.01	1	69	5.8	89.7	0.5	0.01	1
34	6.8	84.9	0.8	0.01	1	70	7.2	375.0	0.5	0.01	1
35	6.8	61.1	0.8	0.01	1	71	6.6	87.1	0.5	0.01	1
36	5.4	62.2	0.8	0.01	1			**Total**	69.6	1.00	100

Table 4-7 Selected Scenarios: 10% Probability of Exceedance in 50 Yrs. (Long Ensemble, 100 events/bin)

Scenario No.	M_w	R (km)	Contr (%)	Proportn	No. of Events	Scenario No.	M_w	R (km)	Contr (%)	Proportn	No. of Events
1	5.4	35.4	2.1	0.03	3	39	6.0	356.4	0.7	0.01	1
2	7.4	416.1	1.7	0.03	3	40	6.4	60.7	0.6	0.01	1
3	5.0	13.8	1.6	0.03	3	41	6.8	276.4	0.6	0.01	1
4	5.4	15.5	1.6	0.03	3	42	6.4	85.1	0.6	0.01	1
5	5.8	36.9	1.6	0.03	3	43	5.6	122.0	0.6	0.01	1
6	5.6	35.9	1.6	0.02	2	44	6.2	177.4	0.6	0.01	1
7	6.8	393.5	1.5	0.02	2	45	7.4	780.9	0.6	0.01	1
8	5.0	33.4	1.4	0.02	2	46	4.8	32.8	0.6	0.01	1
9	6.0	35.7	1.4	0.02	2	47	5.8	88.6	0.6	0.01	1
10	4.8	13.5	1.4	0.02	2	48	6.0	120.0	0.6	0.01	1
11	6.2	35.7	1.3	0.02	2	49	6.2	222.5	0.6	0.01	1
12	6.2	410.3	1.3	0.02	2	50	6.2	339.3	0.6	0.01	1
13	5.8	63.2	1.2	0.02	2	51	6.8	177.1	0.6	0.01	1
14	6.4	388.0	1.2	0.02	2	52	5.6	86.9	0.6	0.01	1
15	7.0	418.2	1.1	0.02	2	53	6.0	171.0	0.6	0.01	1
16	7.2	408.9	1.1	0.02	2	54	6.8	557.8	0.5	0.01	1
17	7.0	357.0	1.1	0.02	2	55	6.8	85.0	0.5	0.01	1
18	5.4	61.7	1.1	0.02	2	56	7.0	726.8	0.5	0.01	1
19	5.2	33.5	1.0	0.02	2	57	5.4	86.7	0.5	0.01	1
20	5.6	62.1	1.0	0.02	1	58	6.0	13.8	0.5	0.01	1
21	7.4	366.6	0.9	0.02	1	59	6.4	439.1	0.5	0.01	1
22	6.2	61.9	0.9	0.02	1	60	4.6	13.9	0.5	0.01	1
23	6.0	62.5	0.9	0.02	1	61	6.4	275.7	0.5	0.01	1
24	6.8	657.5	0.9	0.01	1	62	6.6	36.6	0.5	0.01	1
25	5.8	16.5	0.9	0.01	1	63	5.8	120.7	0.5	0.01	1
26	6.8	405.8	0.9	0.01	1	64	7.0	694.3	0.5	0.01	1
27	5.6	15.4	0.9	0.01	1	65	6.8	712.8	0.5	0.01	1
28	7.4	714.9	0.8	0.01	1	66	6.4	542.7	0.5	0.01	1
29	6.2	123.0	0.8	0.01	1	67	6.8	61.3	0.5	0.01	1
30	6.2	86.0	0.8	0.01	1	68	7.3	911.1	0.5	0.01	1
31	7.0	432.4	0.8	0.01	1	69	6.4	177.0	0.5	0.01	1
32	6.6	407.7	0.8	0.01	1	70	6.2	13.4	0.5	0.01	1
33	5.2	13.7	0.8	0.01	1	71	6.8	122.5	0.5	0.01	1
34	6.4	37.5	0.7	0.01	1	72	7.4	633.9	0.5	0.01	1
35	6.4	121.9	0.7	0.01	1	73	5.8	126.5	0.5	0.01	1
36	6.8	440.1	0.7	0.01	1	74	6.6	585.5	0.5	0.01	1
37	6.8	37.1	0.7	0.01	1	75	7.0	586.7	0.5	0.01	1
38	6.0	86.8	0.7	0.01	1	76	6.6	63.5	0.5	0.01	1
								Total	62.7	1.00	100

Table 4-8 Selected Scenarios: 20% Probability of Exceedance in 50 Yrs. (Long Ensemble, 100 events/bin)

Scenario No.	M_w	R (km)	Contr (%)	Proportn	No. of Events	Scenario No.	M_w	R (km)	Contr (%)	Proportn	No. of Events
1	5.4	35.4	1.9	0.03	3	38	6.2	122.1	0.7	0.01	1
2	6.4	417.6	1.8	0.03	3	39	7.0	761.7	0.6	0.01	1
3	6.8	415.2	1.8	0.03	3	40	6.8	741.4	0.6	0.01	1
4	7.4	392.3	1.6	0.03	3	41	5.4	88.2	0.6	0.01	1
5	5.0	35.3	1.5	0.03	3	42	7.0	398.5	0.6	0.01	1
6	5.0	15.7	1.4	0.02	3	43	6.2	62.6	0.6	0.01	1
7	6.2	413.0	1.3	0.02	2	44	5.2	15.5	0.6	0.01	1
8	5.4	62.9	1.2	0.02	2	45	7.2	431.7	0.6	0.01	1
9	4.8	13.8	1.2	0.02	2	46	5.4	120.2	0.6	0.01	1
10	5.8	408.8	1.1	0.02	2	47	5.8	177.5	0.6	0.01	1
11	5.6	35.9	1.1	0.02	2	48	7.0	664.6	0.6	0.01	1
12	4.8	33.4	1.1	0.02	2	49	6.4	569.6	0.6	0.01	1
13	5.8	36.0	1.1	0.02	2	50	4.6	14.6	0.6	0.01	1
14	6.8	692.0	1.1	0.02	2	51	6.8	353.6	0.6	0.01	1
15	6.0	393.5	1.1	0.02	2	52	6.0	177.3	0.6	0.01	1
16	6.2	367.0	1.1	0.02	2	53	5.2	62.6	0.5	0.01	1
17	5.8	64.3	1.0	0.02	2	54	7.0	726.3	0.5	0.01	1
18	5.6	63.6	0.9	0.02	2	55	6.4	123.9	0.5	0.01	1
19	7.4	691.2	0.9	0.02	2	56	7.0	677.1	0.5	0.01	1
20	7.0	410.2	0.9	0.02	2	57	5.8	90.0	0.5	0.01	1
21	5.2	35.9	0.9	0.02	2	58	6.2	86.6	0.5	0.01	1
22	5.4	14.5	0.8	0.01	1	59	7.3	935.3	0.5	0.01	1
23	6.0	35.9	0.8	0.01	1	60	5.8	222.6	0.5	0.01	1
24	6.8	586.0	0.8	0.01	1	61	6.0	544.7	0.5	0.01	1
25	7.4	792.1	0.8	0.01	1	62	6.6	389.5	0.5	0.01	1
26	6.6	418.8	0.8	0.01	1	63	5.6	89.2	0.5	0.01	1
27	5.8	122.7	0.7	0.01	1	64	6.8	436.1	0.5	0.01	1
28	5.0	62.2	0.7	0.01	1	65	6.8	124.8	0.5	0.01	1
29	6.0	64.5	0.7	0.01	1	66	6.2	699.0	0.5	0.01	1
30	7.4	755.0	0.7	0.01	1	67	7.2	361.0	0.5	0.01	1
31	6.2	36.1	0.7	0.01	1	68	6.0	410.7	0.5	0.01	1
32	6.4	342.6	0.7	0.01	1	69	6.6	762.3	0.5	0.01	1
33	6.4	711.7	0.7	0.01	1	70	7.2	700.0	0.5	0.01	1
34	6.0	122.1	0.7	0.01	1	71	6.6	539.8	0.5	0.01	1
35	7.0	444.3	0.7	0.01	1	72	5.8	337.7	0.5	0.01	1
36	7.3	906.7	0.7	0.01	1	73	6.2	445.1	0.5	0.01	1
37	6.2	608.5	0.7	0.01	1			**Total**	57.2	1.00	100

4.3 Simulation Procedure

The simulation of ENA strong ground motions does not require the generation of a pulse, as discussed in Section 3. Hence, the simulation procedure is simpler and involves the following steps:

Step 1: Generate a time history using the Specific Barrier Model

For each earthquake scenario (magnitude-distance pair), generate the time histories using the SBM (refer to Section 2). The time histories with the highest and the second highest peak spectra are chosen as the fault-normal and the fault-parallel components, respectively. By varying the seed numbers, different far-field time histories can be generated.

Step 2: Calculate the mean response spectra
For each group (short or long version), calculate the "mean" acceleration spectrum of all simulated fault-normal components. This mean spectrum is used for the scaling of the simulated time histories.

Step 3: Scale the simulated time histories
Similar to the case of near-field ground motions, the scaling factor for the earthquakes in each ensemble can be obtained by minimizing the square root sum square of the errors between the scaled "mean" response spectra and the USGS uniform hazard spectra at periods of 0.1, 0.2, 0.3, 0.5, and 1.0 seconds. The same factors apply for the fault-parallel components.

4.4 Resulting Simulated Ground Motions

As an example, the simulation of a 6.2 M_w, 36.3 km scenario for a hazard level of 2% probability of exceedance in 50 years is presented in this section. Figure 4-3 depicts the unscaled and scaled "mean" acceleration spectra compared with the USGS uniform hazard spectrum.

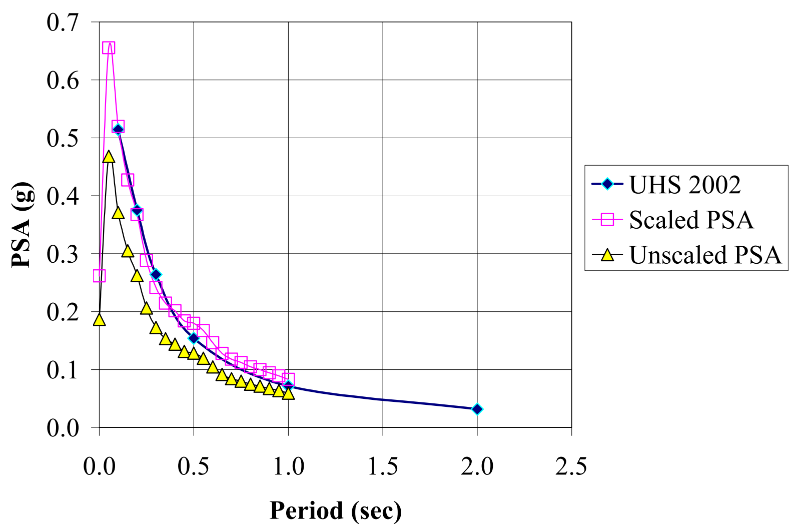


Figure 4-3 Scaling of Mean Response Spectra: Short Ensemble, 2% Probability of Exceedance in 50 Yrs (6.2 M_w, 36.3 km)

Table 4-9 summarizes the scaling factors for the simulated ENA earthquakes. Figure 4-4 illustrates both components of the simulated accelerograms. Their corresponding response spectra at 5% damping are shown in Figure 4-5.

Table 4-9 Scaling Factors for Simulations of ENA Earthquakes

Probability of Exceedance in 50 Years	Short Ensemble (50 events/bin)	Long Ensemble (100 events/bin)
2 %	1.40	1.63
5 %	1.45	1.43
10 %	1.01	1.46
20 %	1.55	1.47

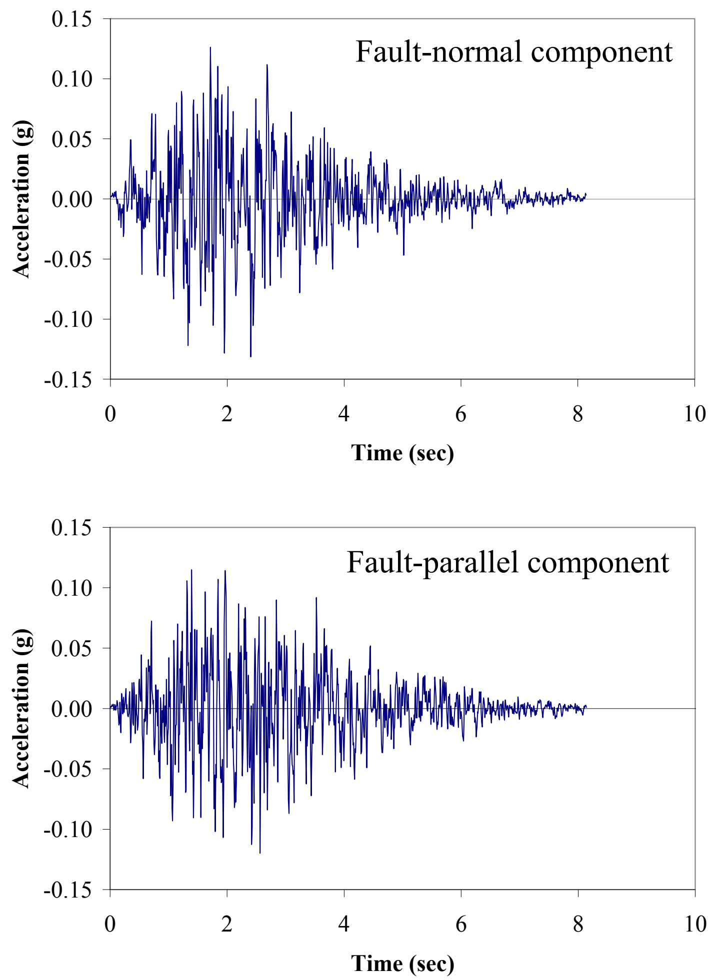


Figure 4-4 Simulated Accelerograms: 2% Probability of Exceedance in 50 Years (6.2 M_w, 36.3 km)

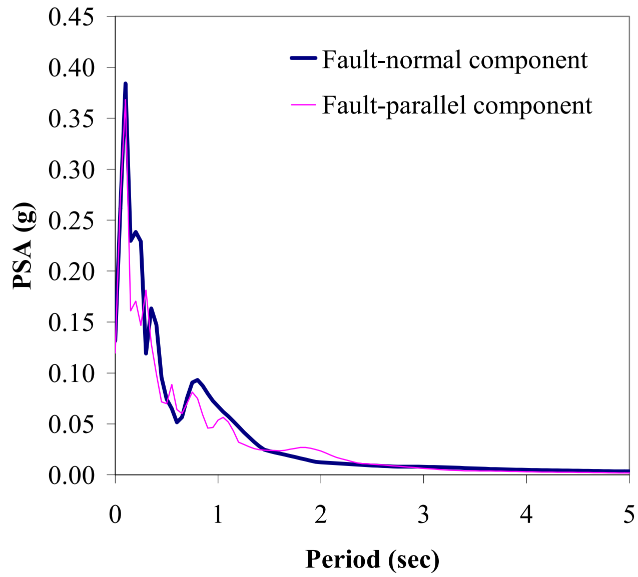


Figure 4-5 Response Spectra at 5% Damping of Simulated Earthquakes: 2% Probability of Exceedance in 50 Years (6.2 M_w, 36.3 km)

Figures 4-6 to 4-9 compare the statistical response spectra of all simulated ground motions for the short ensemble with the USGS uniform hazard spectrum. Comparisons for the long ensemble are illustrated in Figures 4-10 to 4-13. The time histories and their corresponding response spectra at 5% damping of each individual event are summarized in Appendices B and C, for the short and the long ensembles, respectively.

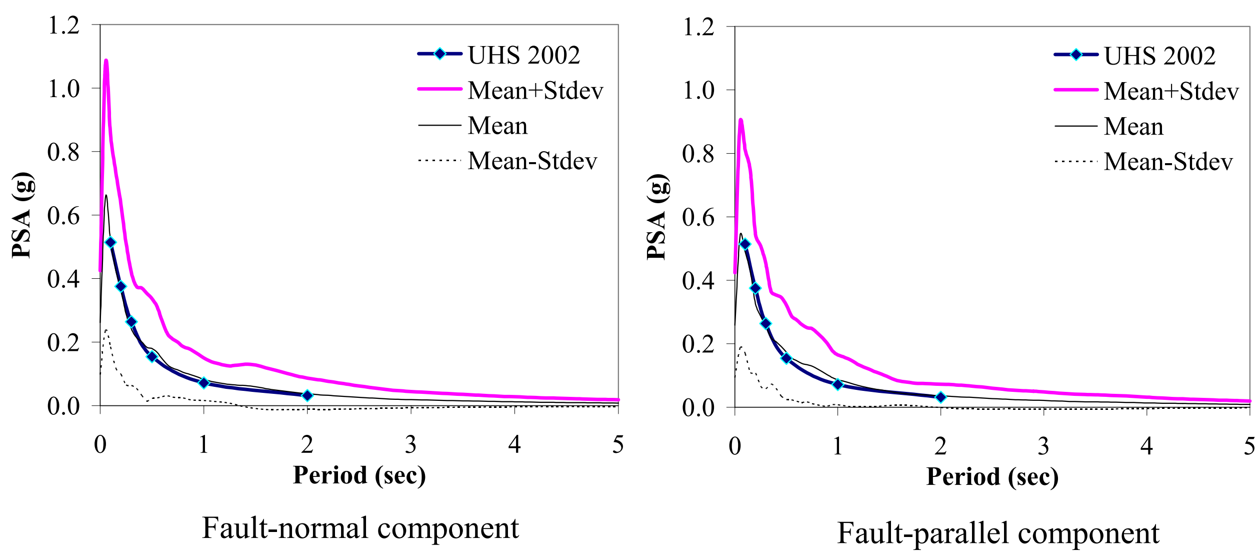
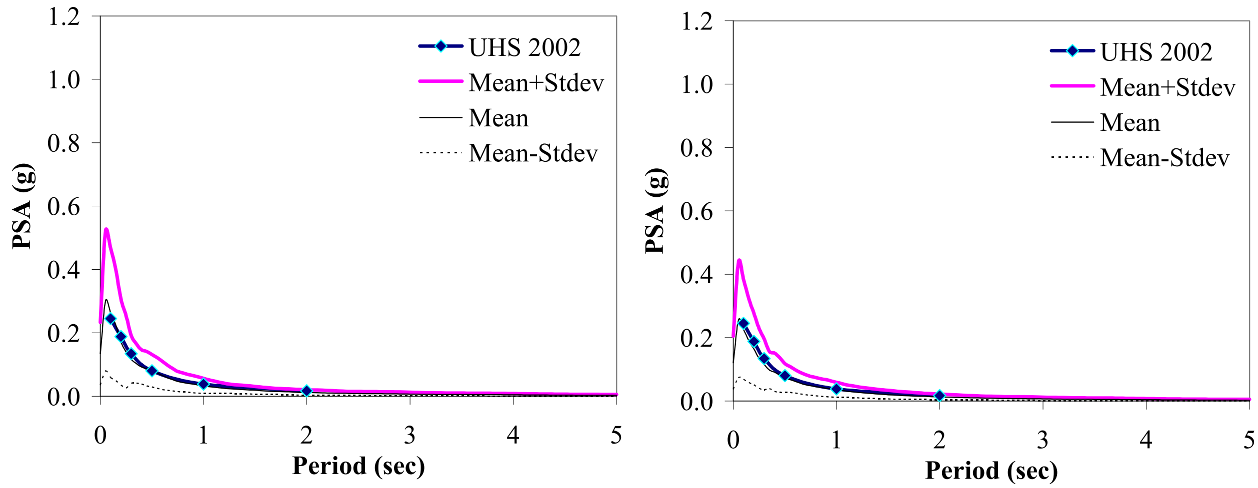


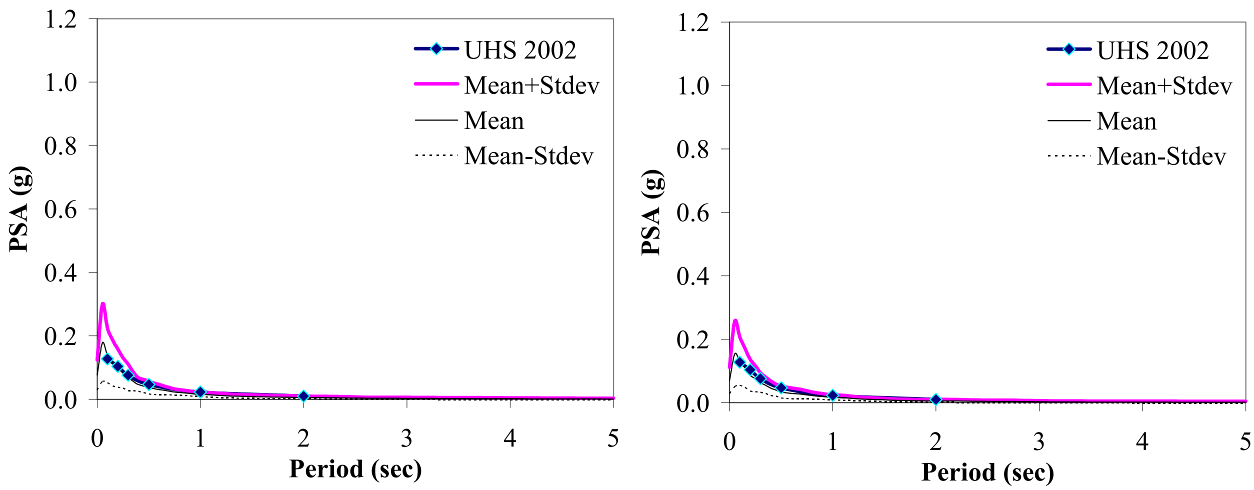
Figure 4-6 Statistical Response Spectra at 5% Damping: Short Ensemble, 2% Probability of Exceedance in 50 Years



Fault-normal component

Fault-parallel component

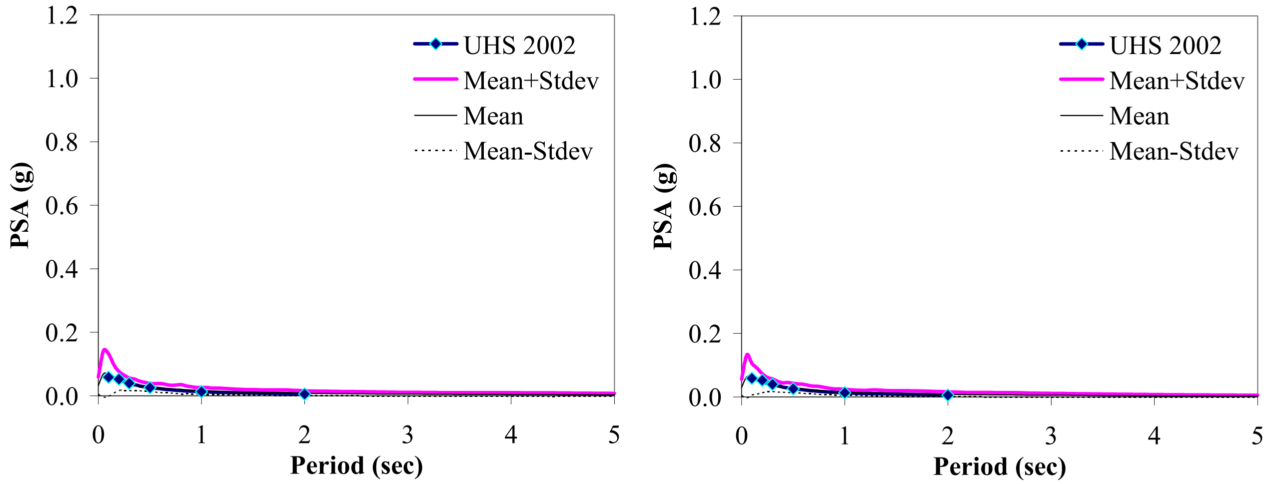
Figure 4-7 Statistical Response Spectra at 5% Damping: Short Ensemble 5% Probability of Exceedance in 50 Years



Fault-normal component

Fault-parallel component

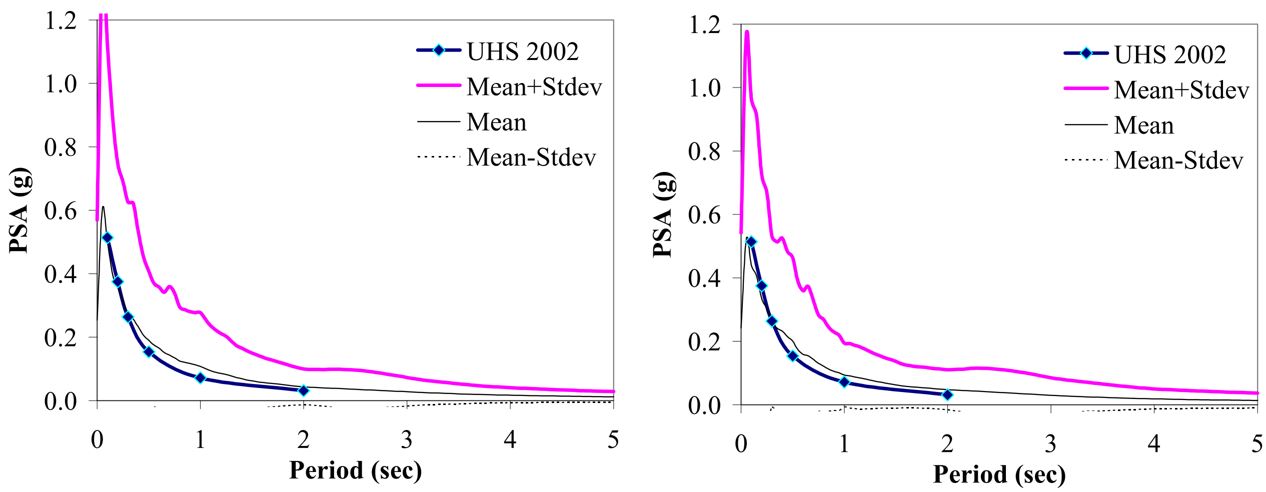
Figure 4-8 Statistical Response Spectra at 5% Damping: Short Ensemble 10% Probability of Exceedance in 50 Years



Fault-normal component

Fault-parallel component

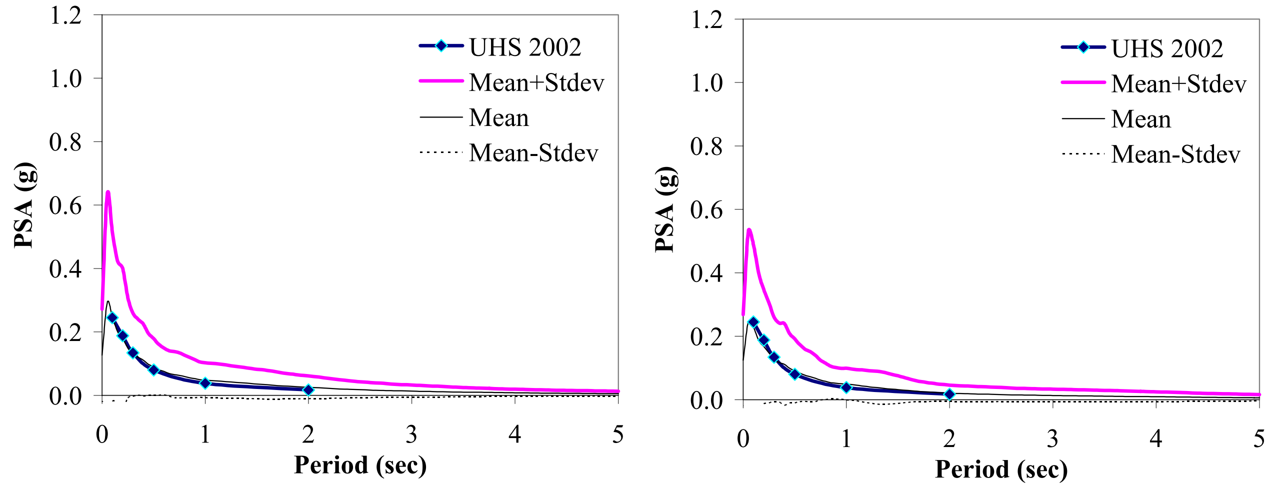
Figure 4-9 Statistical Response Spectra at 5% Damping: Short Ensemble 20% Probability of Exceedance in 50 Years



Fault-normal component

Fault-parallel component

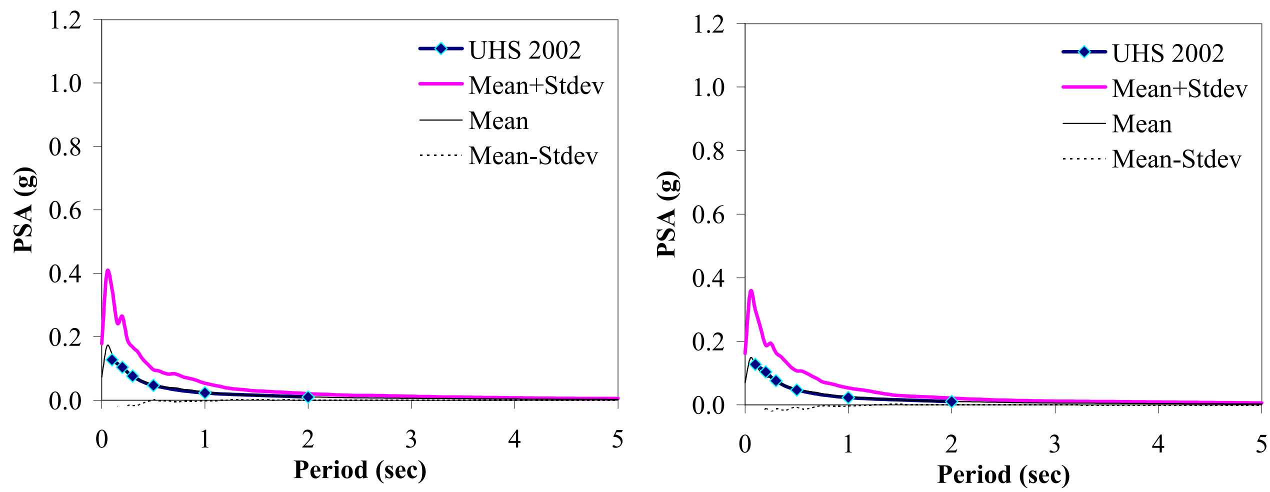
Figure 4-10 Statistical Response Spectra at 5% Damping: Long Ensemble 2% Probability of Exceedance in 50 Years



Fault-normal component

Fault-parallel component

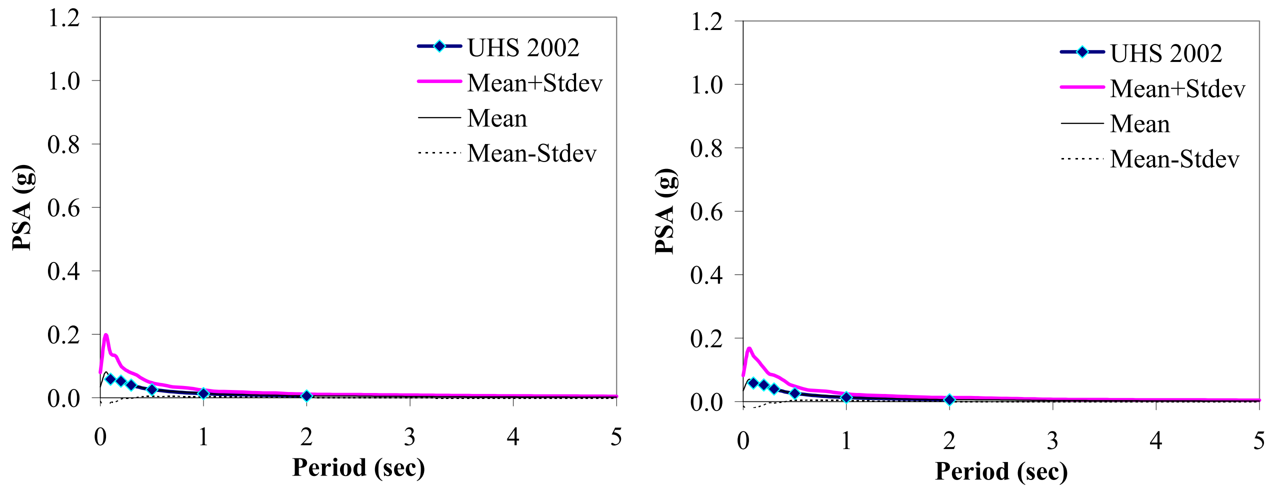
Figure 4-11 Statistical Response Spectra at 5% Damping: Long Ensemble 5% Probability of Exceedance in 50 Years



Fault-normal component

Fault-parallel component

Figure 4-12 Statistical Response Spectra at 5% Damping: Long Ensemble 10% Probability of Exceedance in 50 Years



Fault-normal component

Fault-parallel component

Figure 4-13 Statistical Response Spectra at 5% Damping: Long Ensemble 20% Probability of Exceedance in 50 Years

SECTION 5
SIMULATION OF VERTICAL GROUND MOTIONS

This section presents the procedure adopted for simulation of the vertical ground motions from the corresponding horizontal ground motions generated in Sections 3 and 4.

5.1 Generation of Vertical Acceleration Response Spectra

To simulate a vertical ground motion from its corresponding horizontal component, a vertical acceleration spectrum is needed. This study uses the shifting and reducing technique proposed by Bozorgnia *et al.* (1995, 1996) and recently calibrated by Christopoulos *et al.* (2003), to empirically estimate the vertical response spectrum from its corresponding horizontal acceleration spectrum. The method recognizes the differences in frequency content and amplitude between the horizontal and vertical response spectra. Some details of this method are briefly discussed herein.

Generally, as compared to the horizontal spectra, the peaks of the vertical spectra are usually shifted toward the higher frequency end and they are typically lower than the peaks of those corresponding horizontal spectra. Hence, the vertical spectra can be obtained from the horizontal ones by shifting the horizontal spectra toward the short period range, then reducing their amplitudes. The shifting factor (S_f) is defined as the period axis divider, and the reduction factor (R_f) is defined as the amplitude multiplier. Figure 5-1 illustrates the concept of the shifted and reduced spectra.

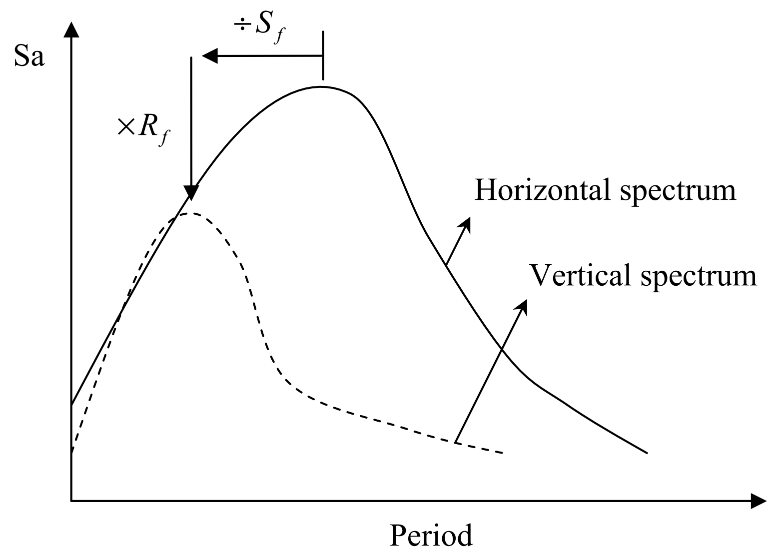


Figure 5-1 The Concept of The Shifted and Reduced Spectra

Christopoulos *et al.* (2003) calibrated shifting and reduction factors by compiling the statistics of an ensemble of 35 historical earthquake records obtained from rock and stiff soils. Earthquakes were divided into two groups according to their source-site distances, with each group having different factors. The first group has a source-to-site distance of 30 km or less, and another group has a distance larger than 30 km. Table 5-1 summarizes the resulting shifting and reduction factors obtained for each group of earthquakes.

Table 5-1 Summary of S_f and R_f

Source-Site Distance	S_f	R_f
≤ 30 km	1.55	0.80
> 30 km	1.60	0.55

Christopoulos *et al.* (2003) defined the correlation factor (θ) as the cosine of the angle between the horizontal and vertical accelerograms:

$$\theta = \frac{\vec{H} \cdot \vec{V}}{\left|\vec{H}\right| \cdot \left|\vec{V}\right|} \tag{5-1}$$

where:

$\vec{H}, \vec{V}$ = the horizontal and vertical accelerograms expressed as (1 x *n*) vectors, *n* is the number of time steps in the accelerograms.

The correlation factor value of 1 indicates that the two accelerograms are not statistically independent, while a value of zero specifies completely uncorrelated components. Table 5-2 presents the average correlation factors obtained from the statistical observation of the earthquakes in the study by Christopoulos *et al*. (2003).

Table 5-2 Average Correlation Factors

Source-Site Distance	**Correlation Factor**
≤ 30 km	0.25
> 30 km	0.12

These correlation factors are applied to correlate the simulated vertical accelerations with their corresponding horizontal ground motions, which is discussed in the following section.

5.2 Simulation Procedure

Once the vertical response spectra are calculated, the computer program RSCTH (Response Spectrum Compatible Time Histories) developed by the Engineering Seismology Laboratory (ESL) at the University at Buffalo is used to generate the spectrum compatible ground motions, which is available for download from the web site at http://civil.eng.buffalo.edu/EngSeisLab/products.htm. The code implements the method described by Deodatis (1996), which utilizes an iterative scheme to generate seismic ground motion time histories with prescribed response spectra. More details can be found in the original document. The procedure for simulating the vertical ground motion is summarized below:

Step 1: Generate the vertical acceleration response spectrum
For each event, a spectrum of a scaled fault-normal horizontal acceleration is selected to generate a vertical response spectrum using the method outlined in the previous section. Note that, for the west coast ground motions, pulses are excluded by using a spectrum of a scaled high-frequency component (refer to Step 6 in Section 3.4).

Step 2: Generate the vertical acceleration-time history
With the prescribed spectra obtained, the vertical time histories can be generated by using the RSCTH code. Note that the durations of the simulated vertical accelerograms are assumed to be equal to their corresponding horizontal ground motions.

Step 3: Correlate the vertical and horizontal accelerations
Calculate the initial correlation factor using Equation (5-1) and compare it with the average value given in Table 5-2 for the corresponding group of earthquakes. If the calculated value is different from the average value more than 30%, the simulated vertical acceleration time history is shifted in time by swapping data at the initial and the end of the record and the correlation factor is re-calculated. A swapping process then iterates until the discrepancy between the calculated and the average correlation factor lies within an acceptable value.

5.3 Resulting Simulated Ground Motions

This section presents, as an example, the resulting simulated vertical accelerograms of the Northridge and the New York (short ensembles) earthquakes with 2% probability of exceedance in 50 years, for each Scenario No. 1, Event No. 1. Figure 5-2 depicts the horizontal response spectrum of the fault-normal component compared with the target and the simulated vertical spectra for the site in Northridge. Comparison for the New York site is shown in Figure 5-3. Figure 5-4 illustrates the simulated horizontal ground motion (fault-normal component) and its corresponding simulated vertical accelerogram for the Northridge earthquake. The results for the New York ground motion are presented in Figure 5-5. All time histories and response spectra of the simulated vertical ground motions for the Northridge and the New York sites are summarized in Appendices B and C, respectively.

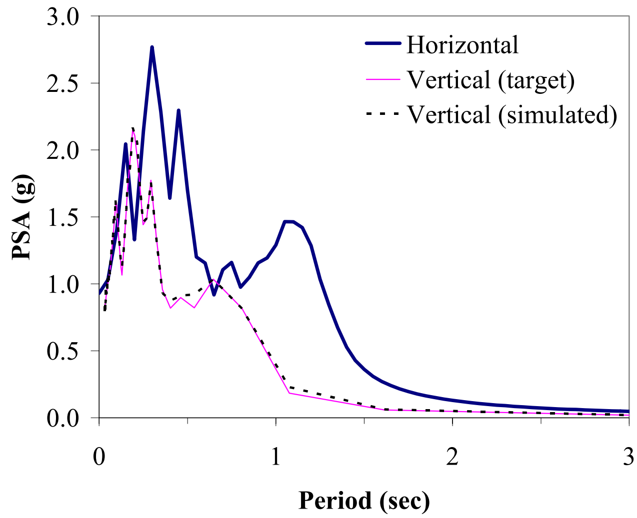


Figure 5-2 Comparison of Response Spectra (5% Damping)
Northridge, 2% Probability of Exceedance (6.6 M_w, 7.5 km)

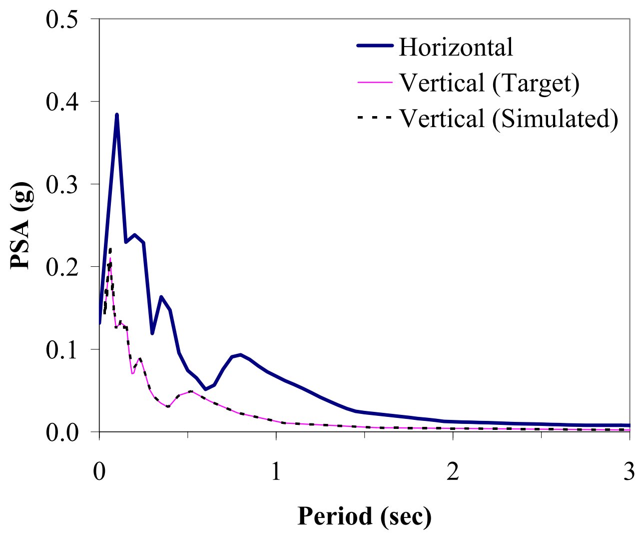


Figure 5-3 Comparison of Response Spectra (5% Damping)
NY (Short Ensemble), 2% Probability of Exceedance (6.2 M_w, 36.3 km)

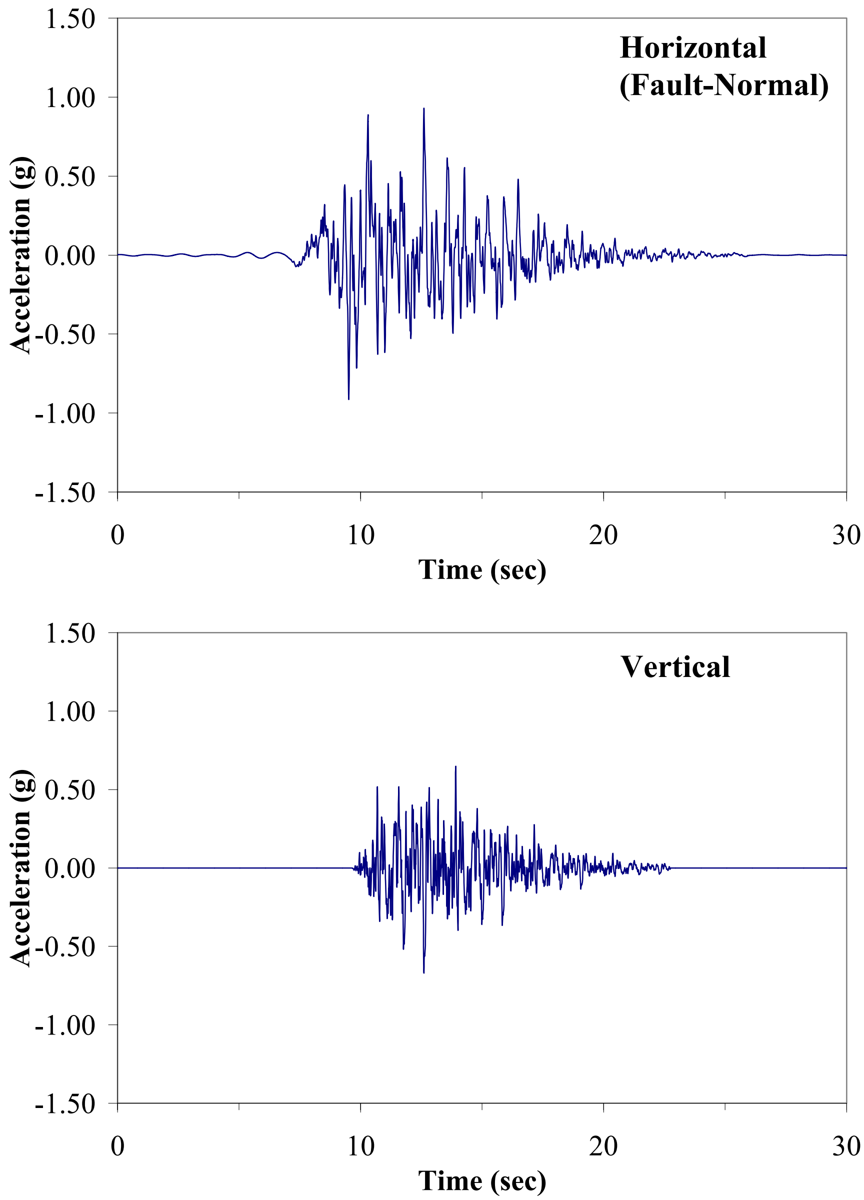


Figure 5-4 The Simulated Horizontal and Vertical Accelerations Northridge, 2% Probability of Exceedance (6.6 M_w, 7.5 km)

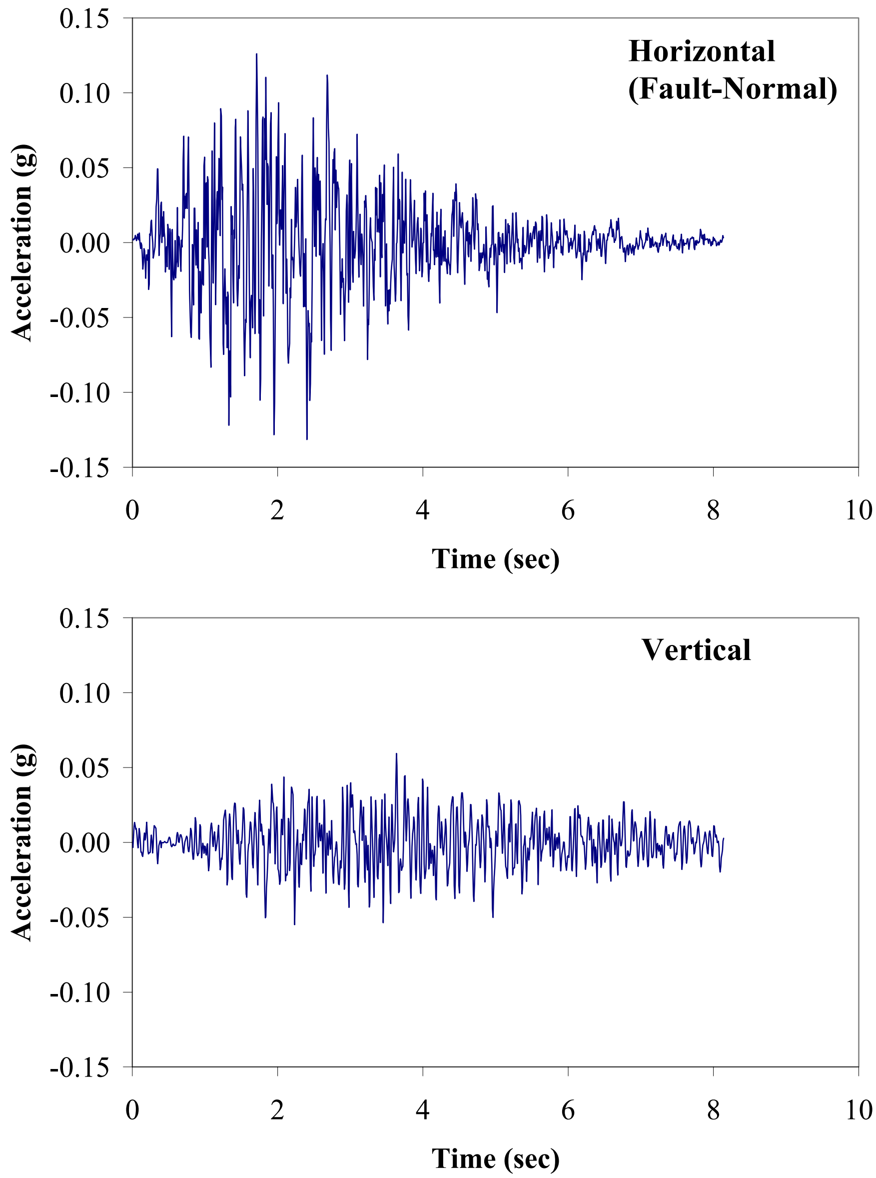


Figure 5-5 The Simulated Horizontal and Vertical Accelerations NY (Short Version), 2% Probability of Exceedance (6.2 M_w, 36.3 km)

SECTION 6
CONCLUSIONS

This study provides ensembles of simulated ground motions representative from scenario earthquake events for hypothetical hospital sites on the west coast and east coast of the United States, respectively. These simulated earthquakes can be utilized in the MCEER Hospital Project research project (Thrust Area 2) for the development of analytical and experimental fragility curves of nonstructural components contained in acute care facilities. The standardized accelerograms generated have four different hazard levels: 2%, 5%, 10% and 20% probabilities of exceedance in 50 years.

The simulation method used in this study is based on a stochastic modeling approach for which strong motion acceleration is modeled as an amplitude-modulated stochastic process, with the spectral content as given by the seismological models corresponding to the calibrated Specific Barrier Model (SBM). The SBM is based on the concept that a strong ground motion is the result of a cumulative contribution of localized cracks distributed on the fault plane, which rupture randomly and independently. Furthermore, "near-fault" velocity pulses were synthesized and combined with the aggregate ground motions resulting from the sub-event simulations. All simulated ground motions are scaled to match the USGS uniform hazard spectrum for a corresponding hazard level.

The shifted and reduced spectra method is utilized to generate the vertical acceleration spectra which are required for simulating the vertical ground motions. With the specified correlation factors, the simulated vertical accelerograms are correlated with their corresponding fault-normal horizontal ground motions by swapping of the data (time shift) in each vertical time history.

A fault configuration similar to the Santa Susana fault in Northridge, California was selected as the prototype configuration for simulating the US west coast accelerations. Pulse motions are included to account for the impulsive nature of the near-fault ground motions; however, they are excluded in the simulation of the corresponding vertical components. For each hazard level, 25 fault-normal and 25 fault-parallel horizontal accelerations with 25 corresponding vertical accelerograms are generated.

For the US east coast, two ensembles of earthquakes are simulated, i.e., a short ensemble which contains 50 earthquakes for each hazard level (50 fault-normal and 50 fault-parallel horizontal accelerations and 50 vertical ground motions) and a long ensemble which contains 100 simulated accelerograms in each ensemble. The short ensemble could be used for experimental programs, while the long ensemble is more appropriate for analytical studies.

SECTION 7
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APPENDIX A
WEST-COAST ACCELEROGRAMS AND RESPONSE SPECTRA

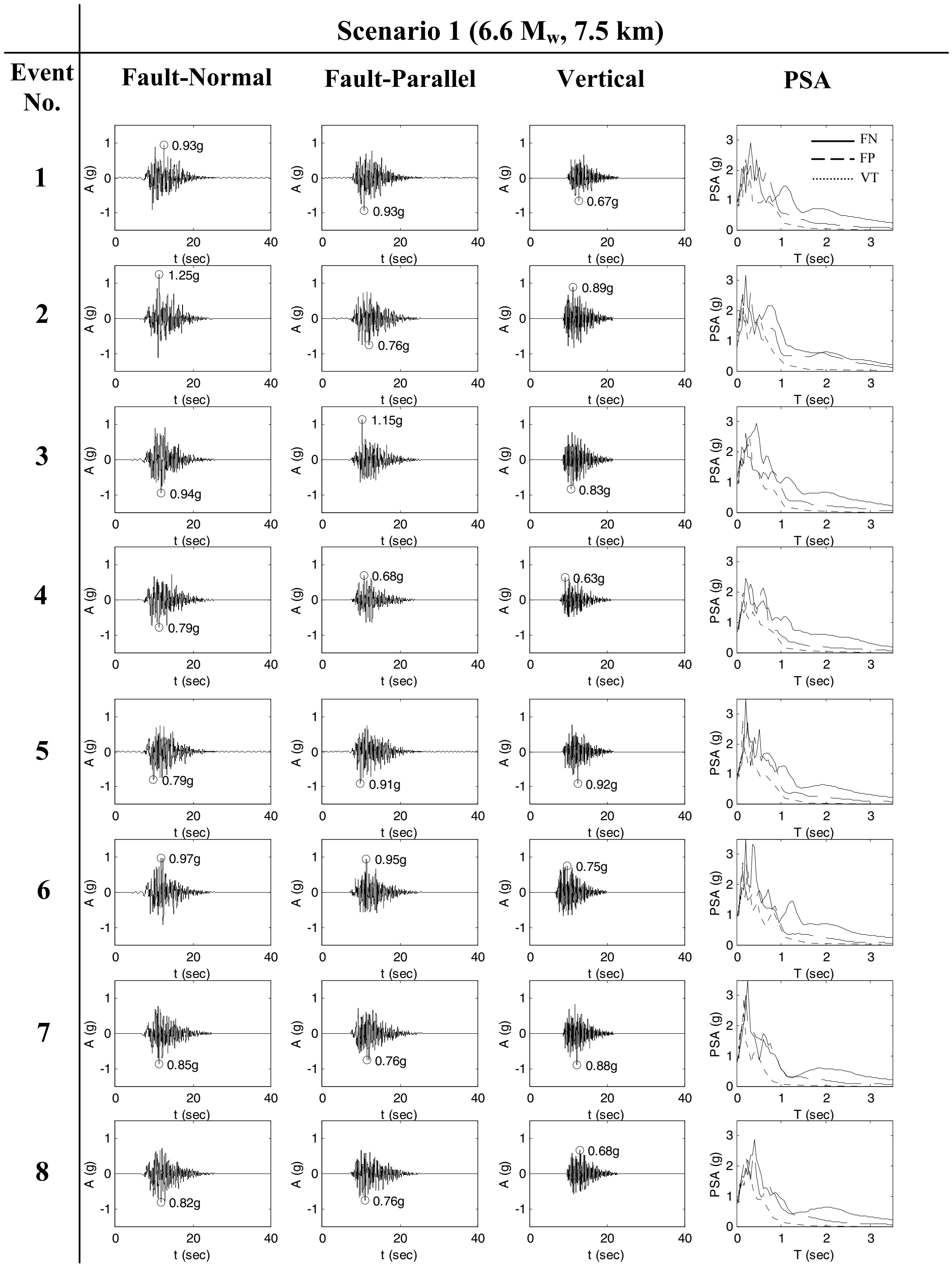


Figure A-1 Northridge : 2% Probability of Exceedance in 50 Years

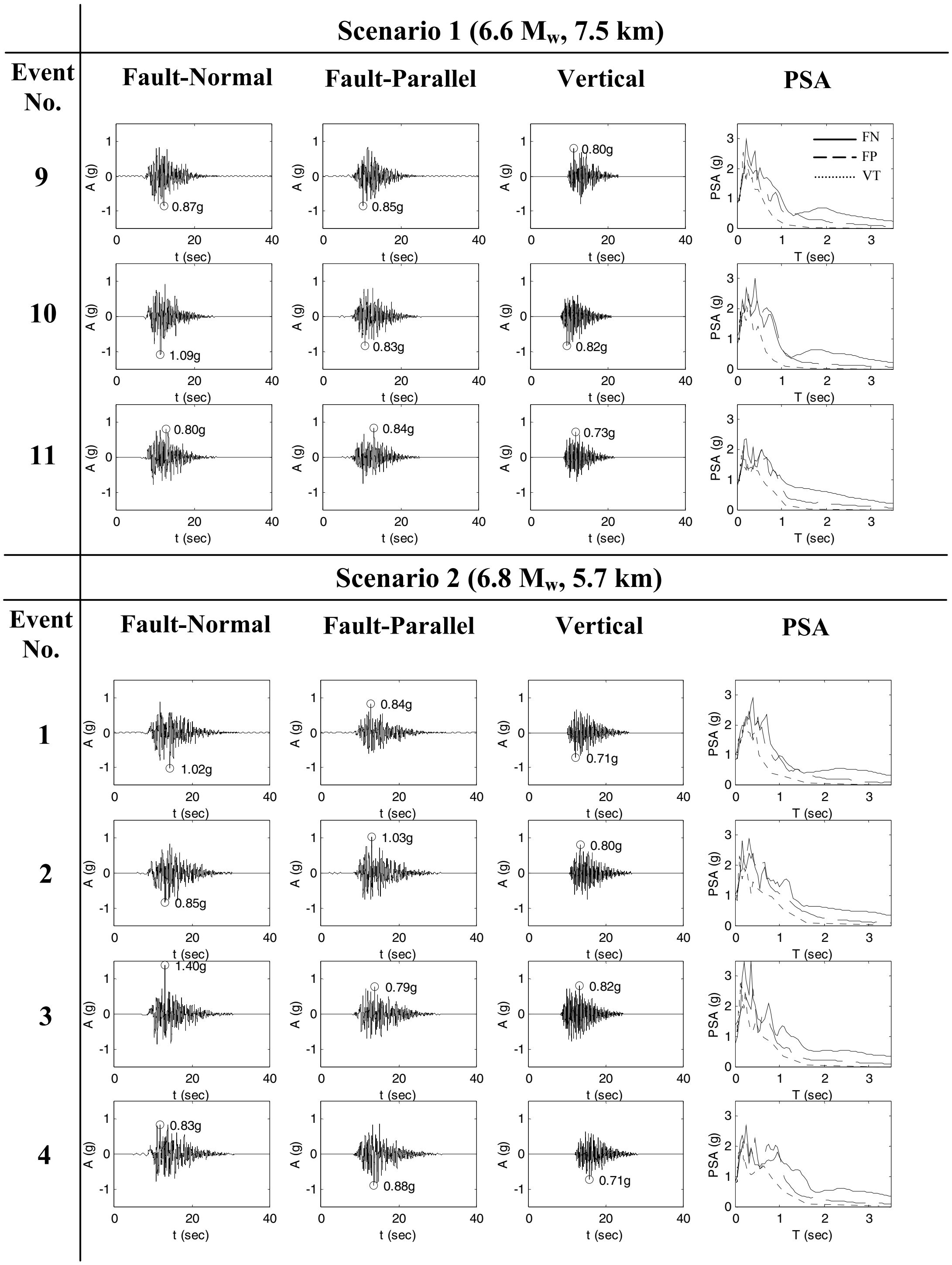


Figure A-1 Northridge : 2% Probability of Exceedance in 50 Years (Cont'd)

Scenario 2 (6.8 M_w, 5.7 km)

Event No. | **Fault-Normal** | **Fault-Parallel** | **Vertical** | **PSA**

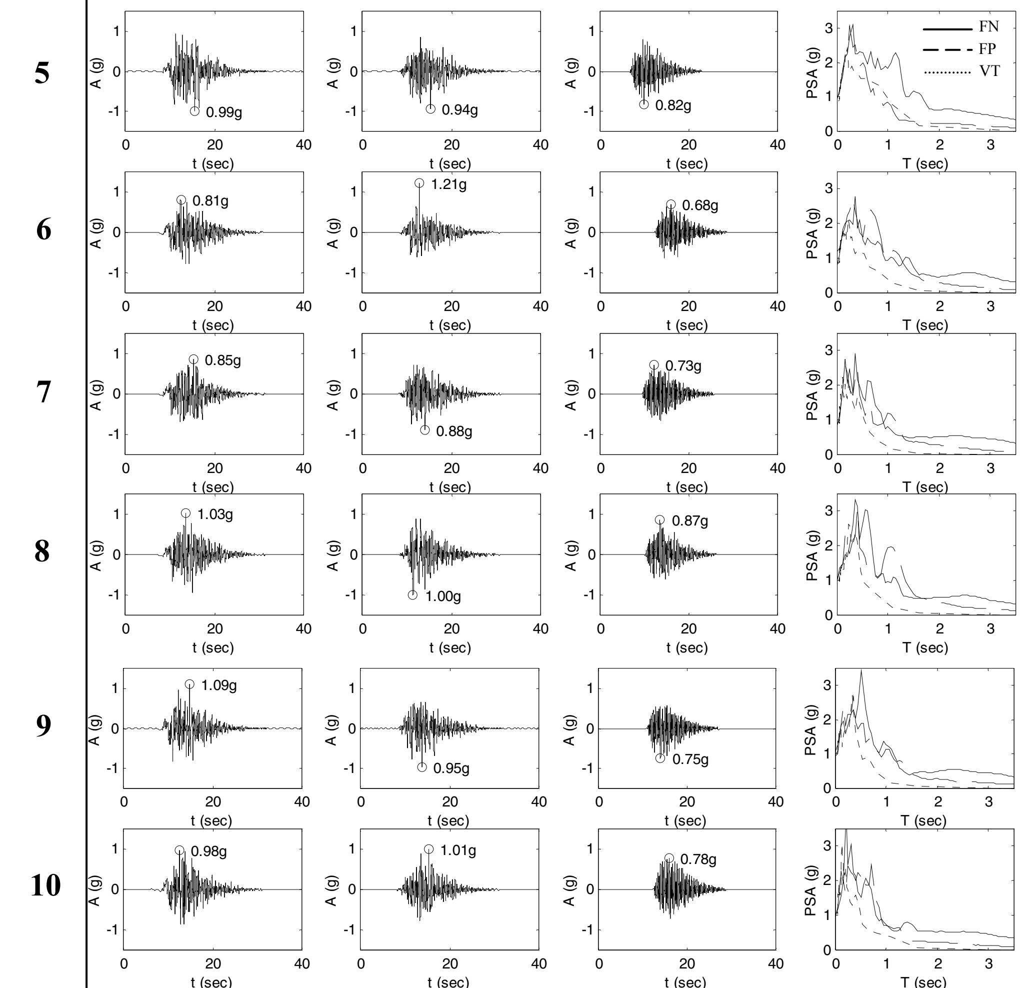


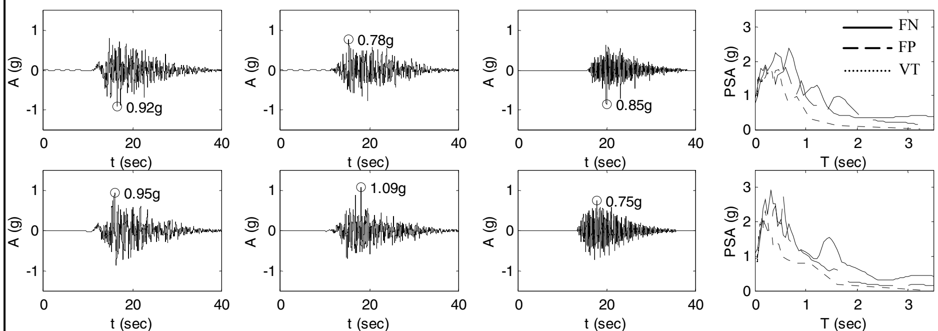
Figure A-1 Northridge : 2% Probability of Exceedance in 50 Years (Cont'd)

Scenario 3 (7.1 M_w, 4.6 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA

1

2



Scenario 4 (6.5 M_w, 7.5 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA

1

2

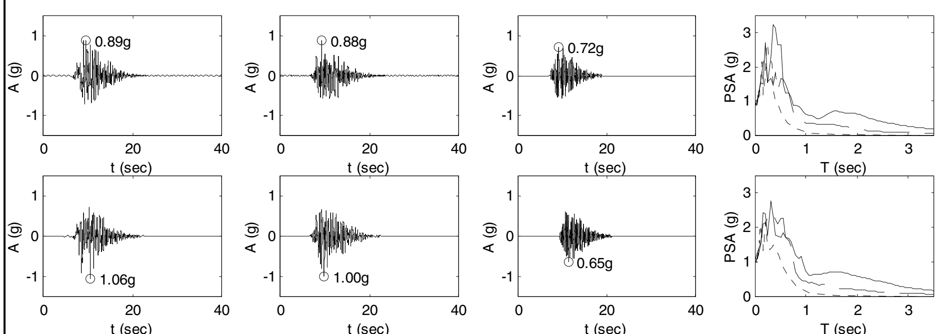


Figure A-1 Northridge : 2% Probability of Exceedance in 50 Years (Cont'd)

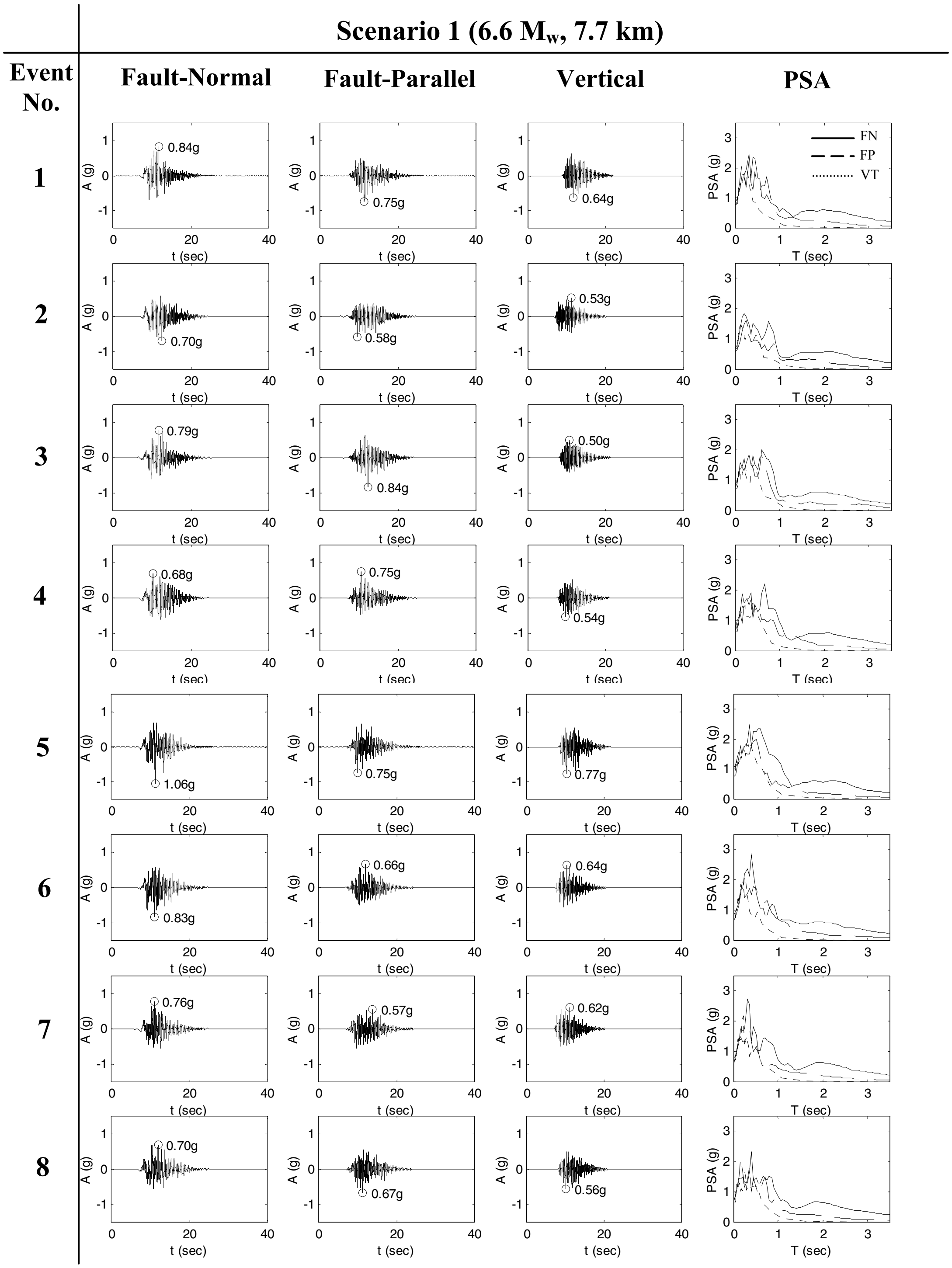


Figure A-2 Northridge : 5% Probability of Exceedance in 50 Years

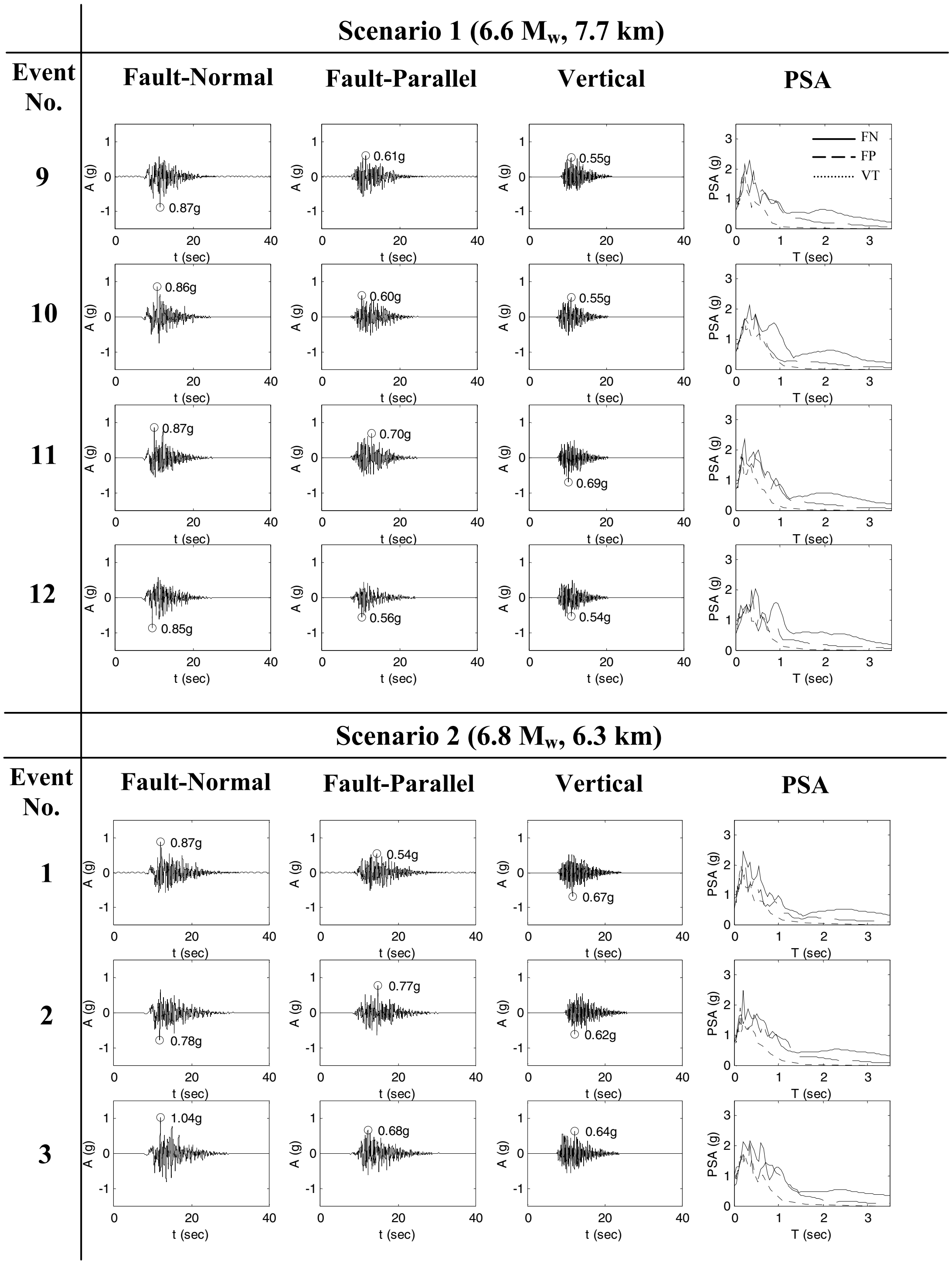


Figure A-2 Northridge : 5% Probability of Exceedance in 50 Years (Cont'd)

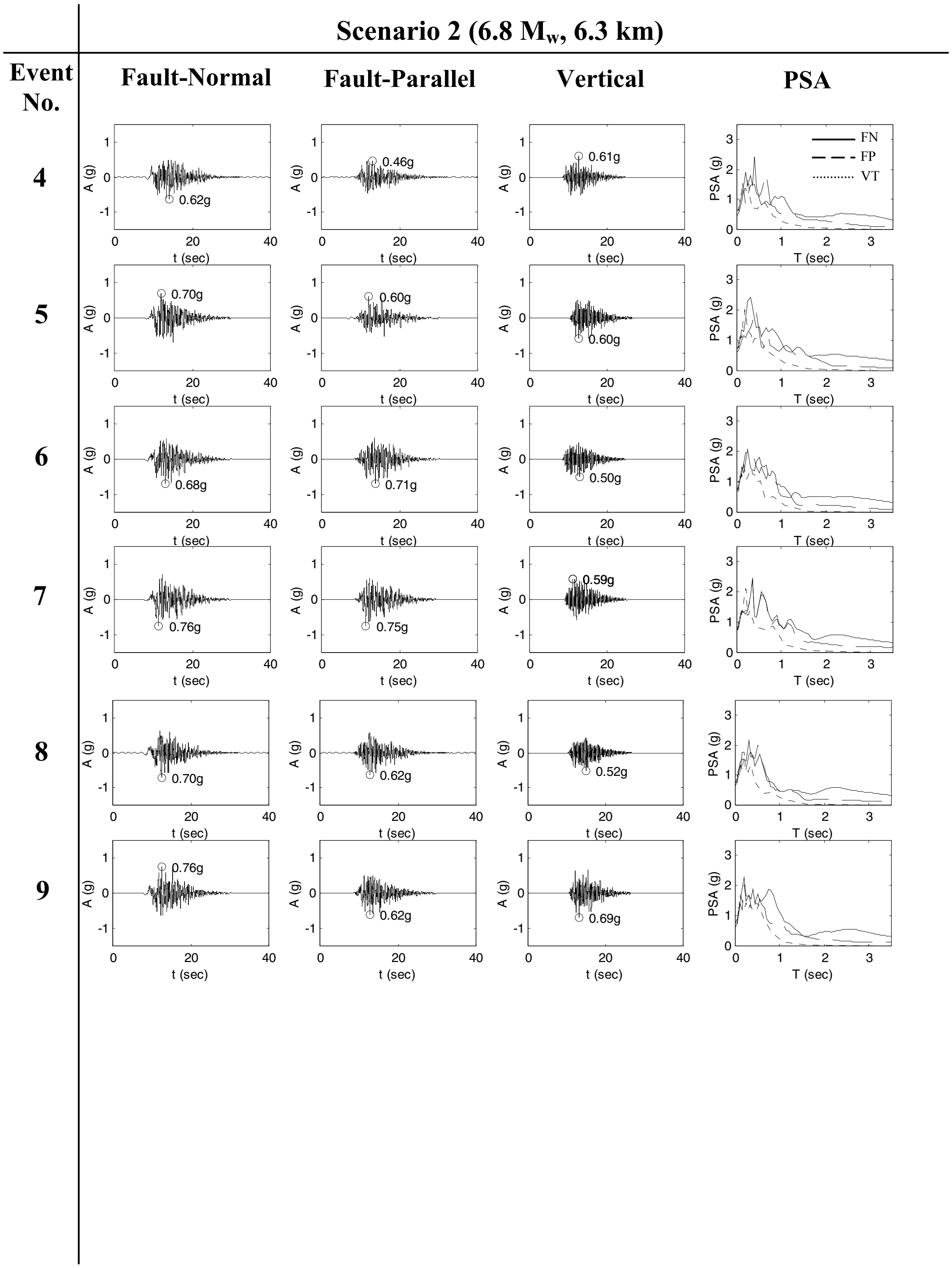
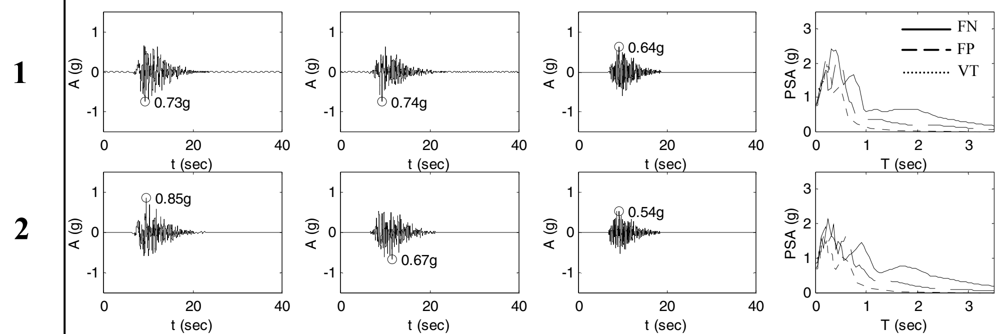


Figure A-2 Northridge : 5% Probability of Exceedance in 50 Years (Cont'd)

Scenario 3 (6.5 M_w, 7.5 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA



Scenario 4 (7.1 M_w, 5.5 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA

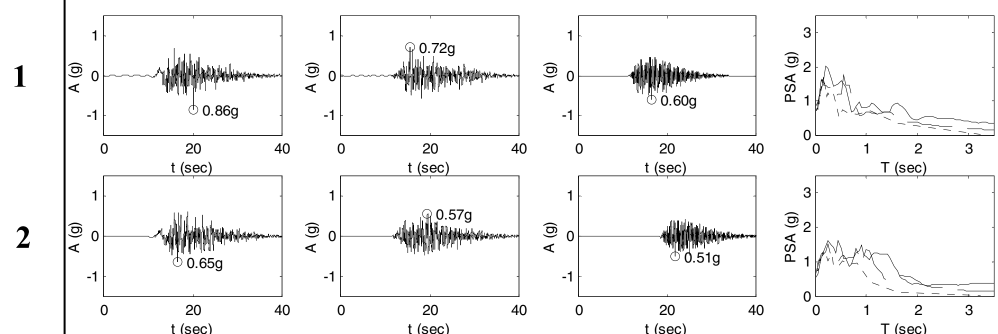


Figure A-2 Northridge : 5% Probability of Exceedance in 50 Years (Cont'd)

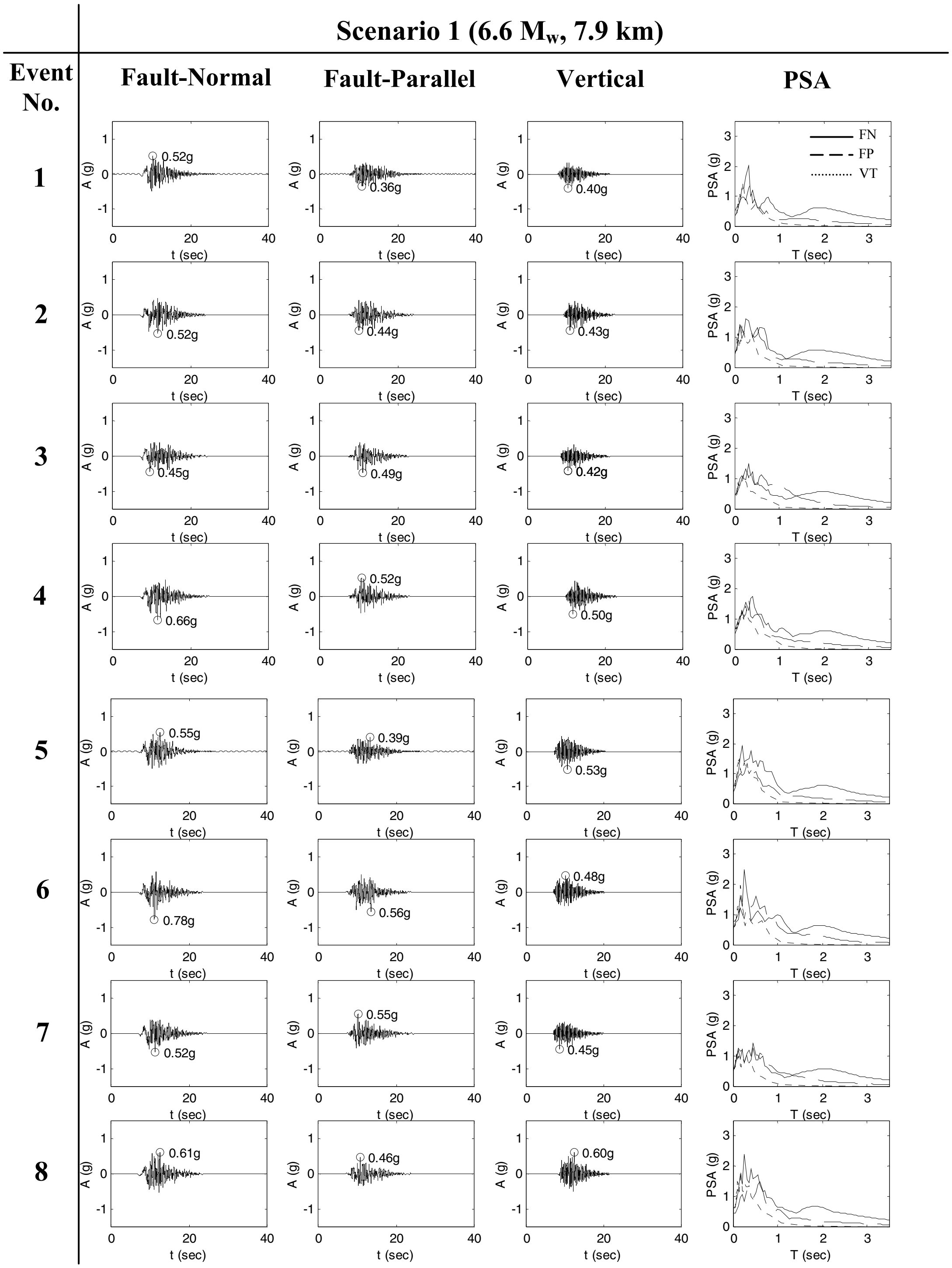


Figure A-3 Northridge : 10% Probability of Exceedance in 50 Years

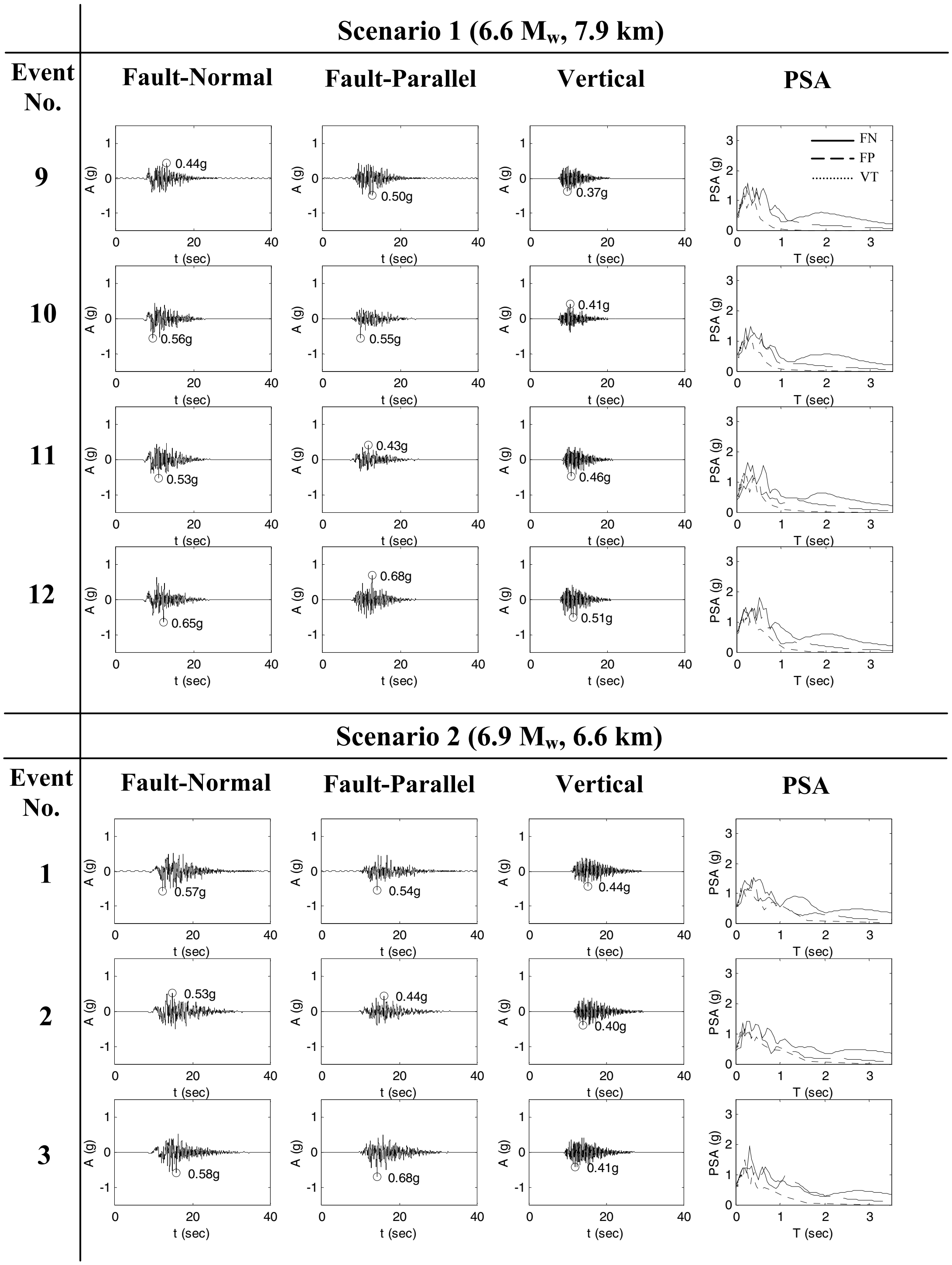


Figure A-3 Northridge : 10% Probability of Exceedance in 50 Years (Cont'd)

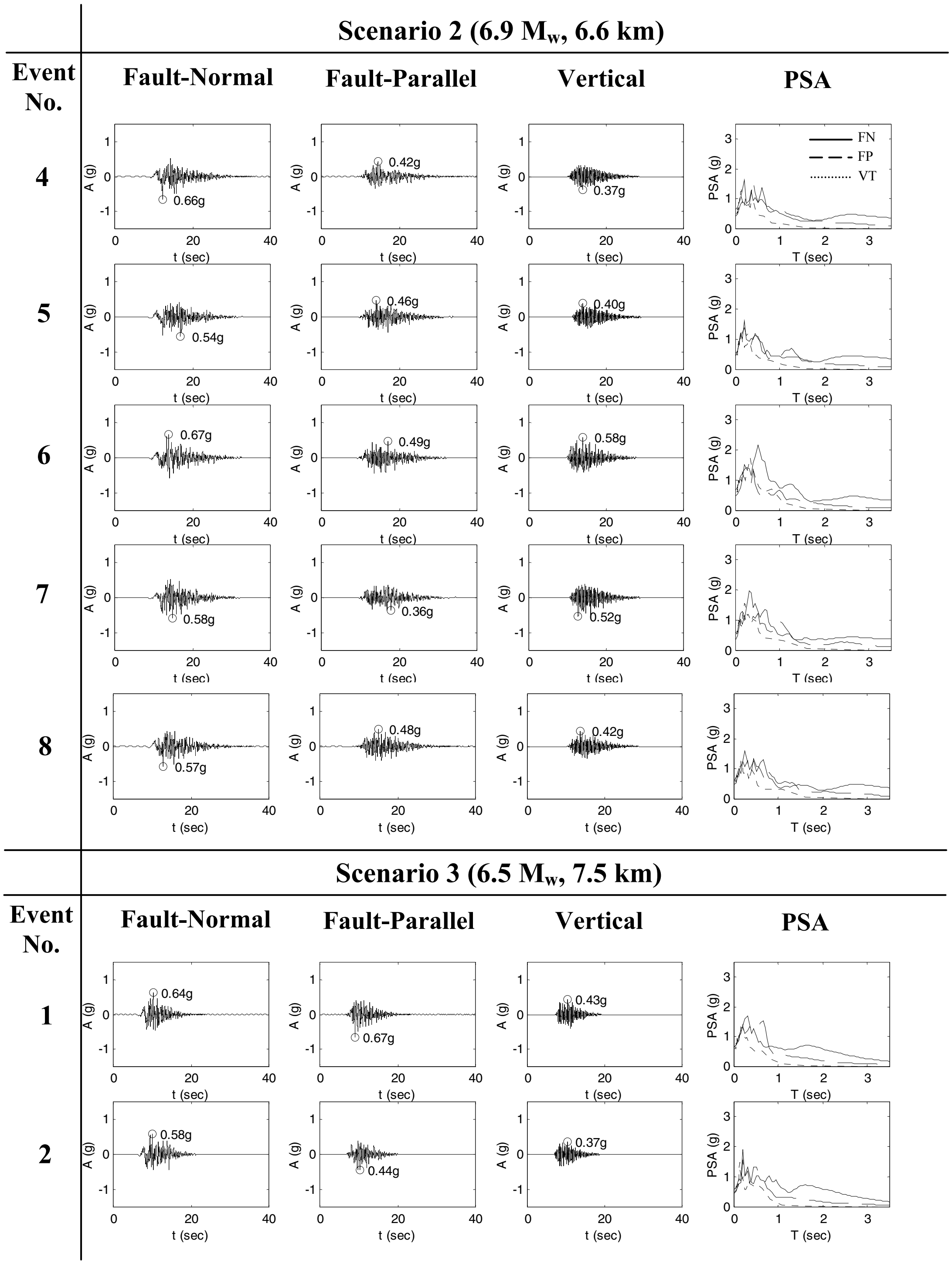
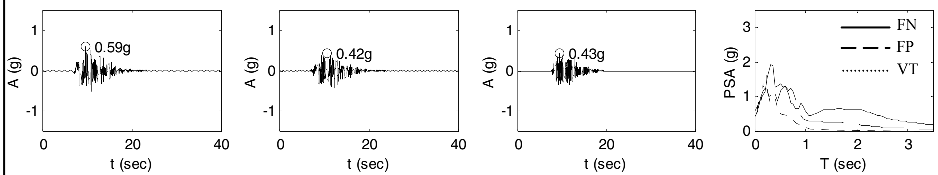


Figure A-3 Northridge : 10% Probability of Exceedance in 50 Years (Cont'd)

Scenario 3 (6.5 M_w, 7.5 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
3				



Scenario 4 (7.1 M_w, 6.4 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				
2				

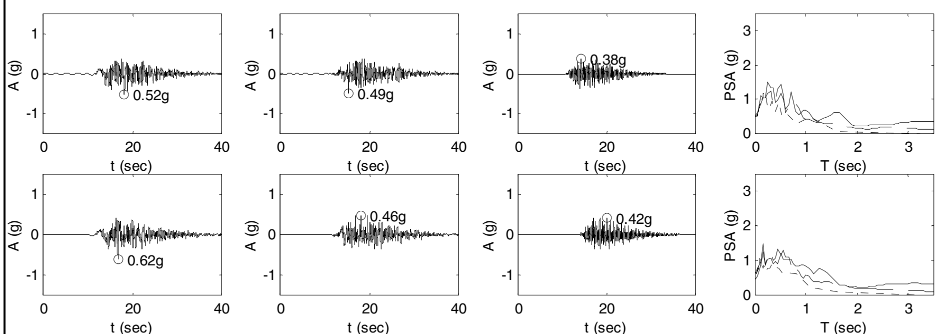


Figure A-3 Northridge : 10% Probability of Exceedance in 50 Years (Cont'd)

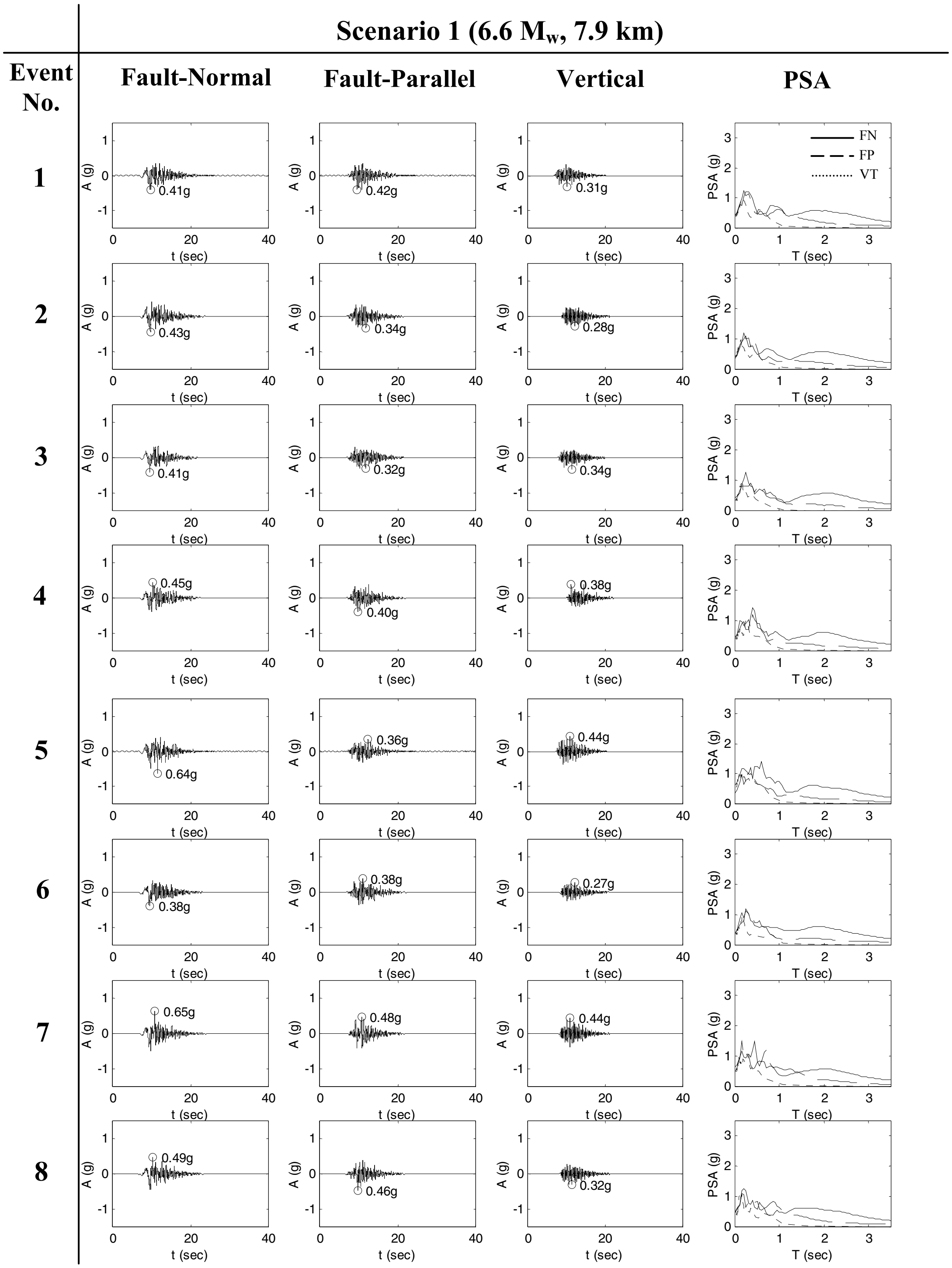


Figure A-4 Northridge : 20% Probability of Exceedance in 50 Years

Scenario 1 (6.6 M_w, 7.9 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA

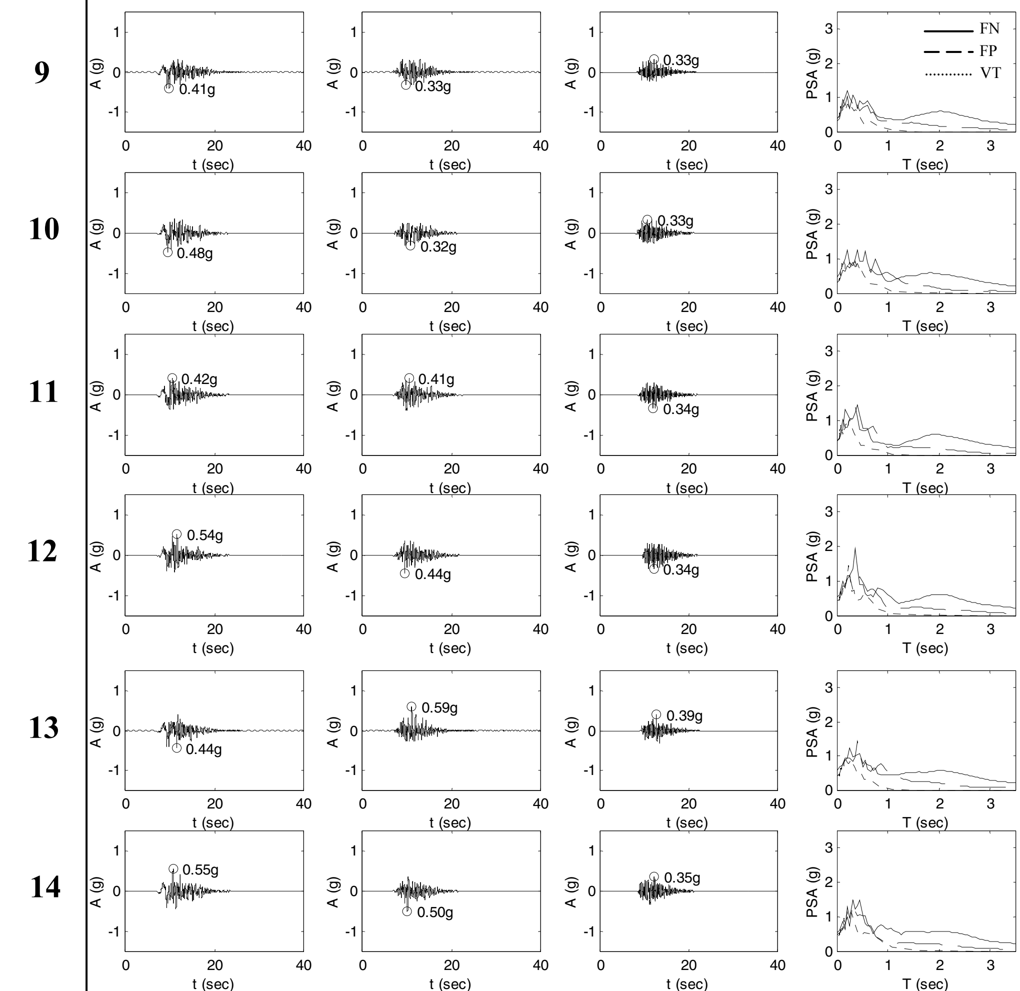


Figure A-4 Northridge : 20% Probability of Exceedance in 50 Years (Cont'd)

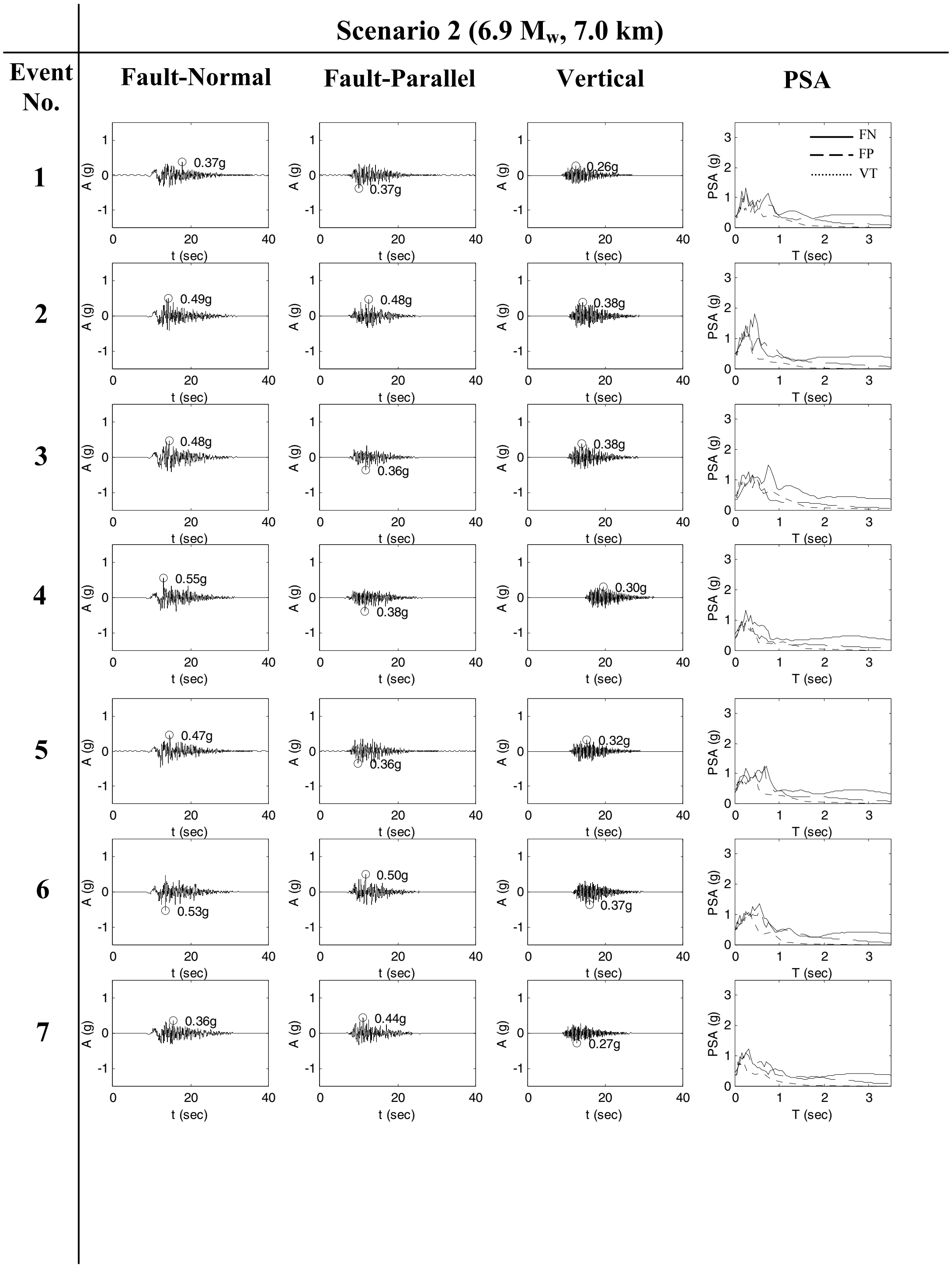
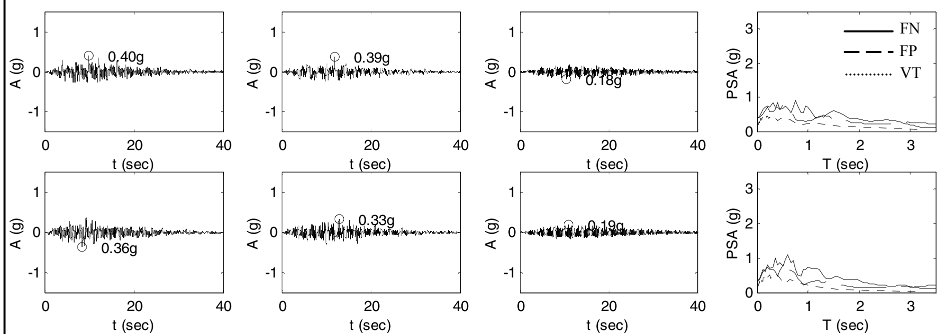


Figure A-4 Northridge : 20% Probability of Exceedance in 50 Years (Cont'd)

Scenario 3 (7.8 M_w, 47.2 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				
2				



Scenario 4 (6.5 M_w, 8.2 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				
2				

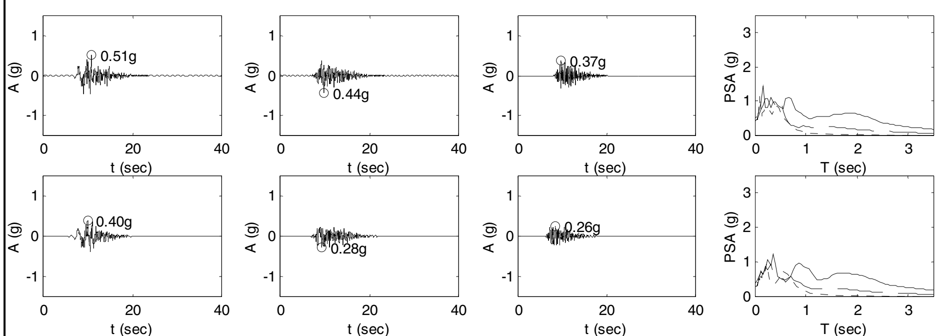


Figure A-4 Northridge : 20% Probability of Exceedance in 50 Years (Cont'd)

APPENDIX B
EAST-COAST ACCELEROGRAMS AND RESPONSE SPECTRA
(SHORT ENSEMBLE)

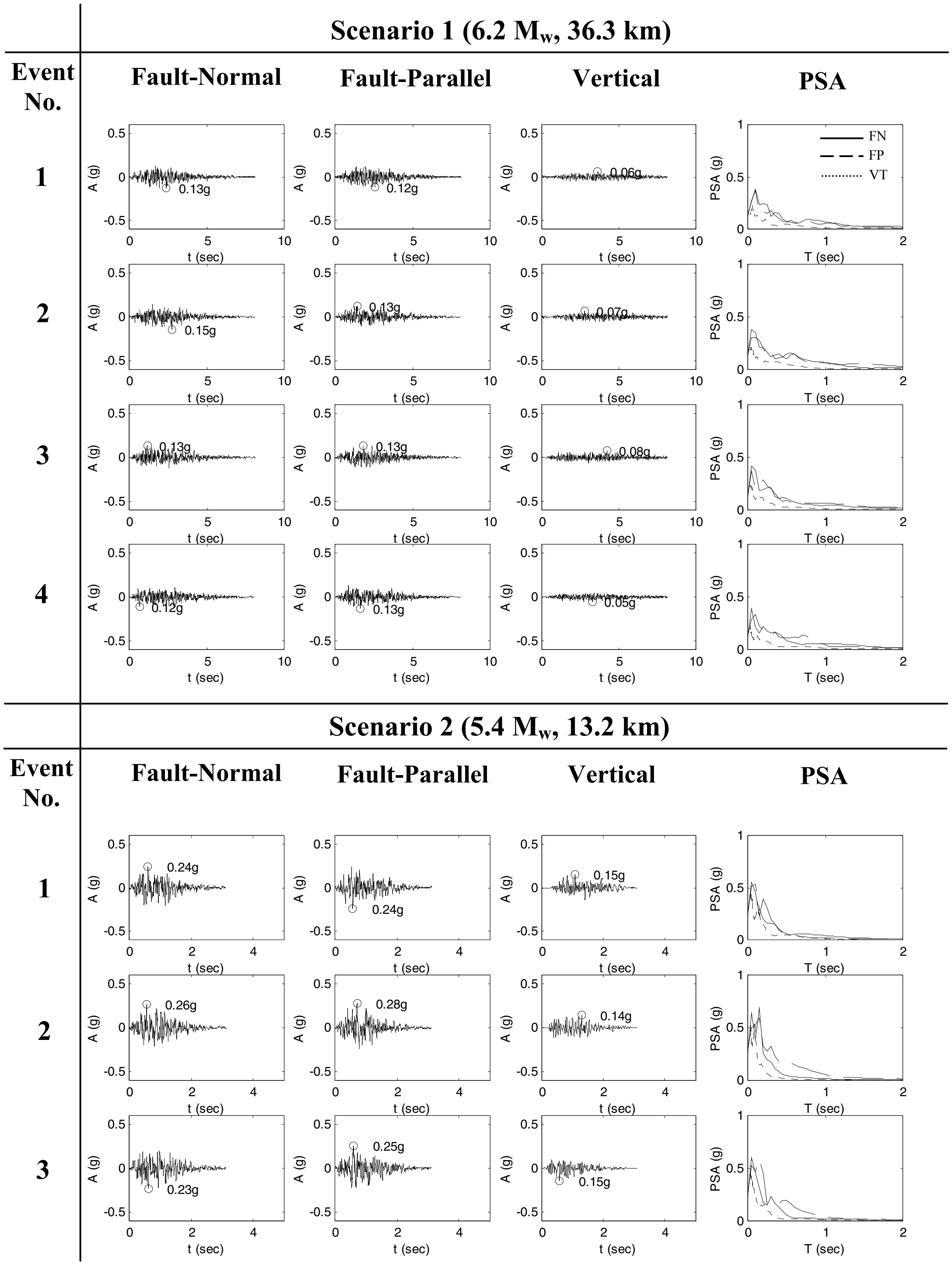


Figure B-1 New York : 2% Probability of Exceedance in 50 Years
Short Ensemble

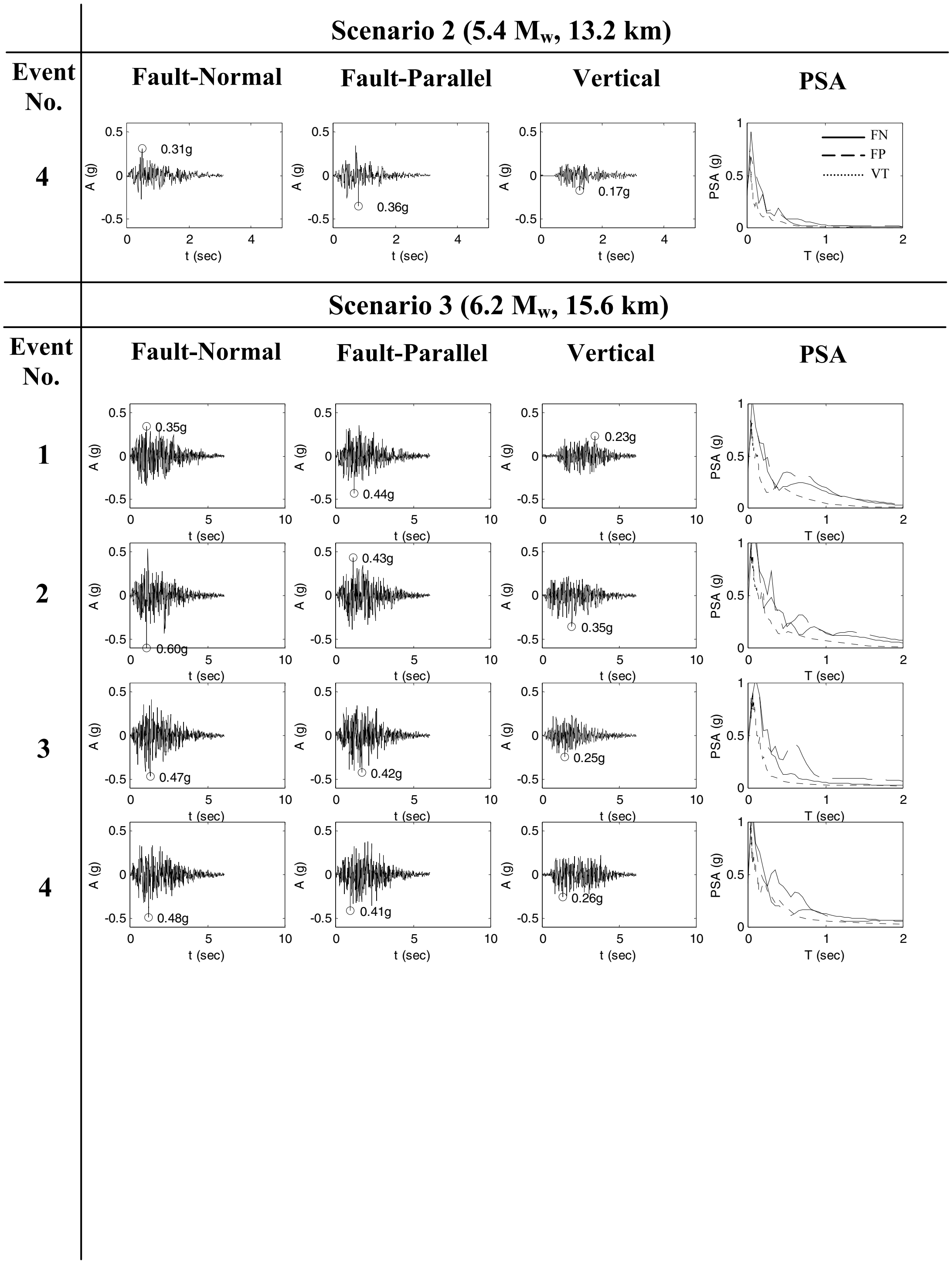
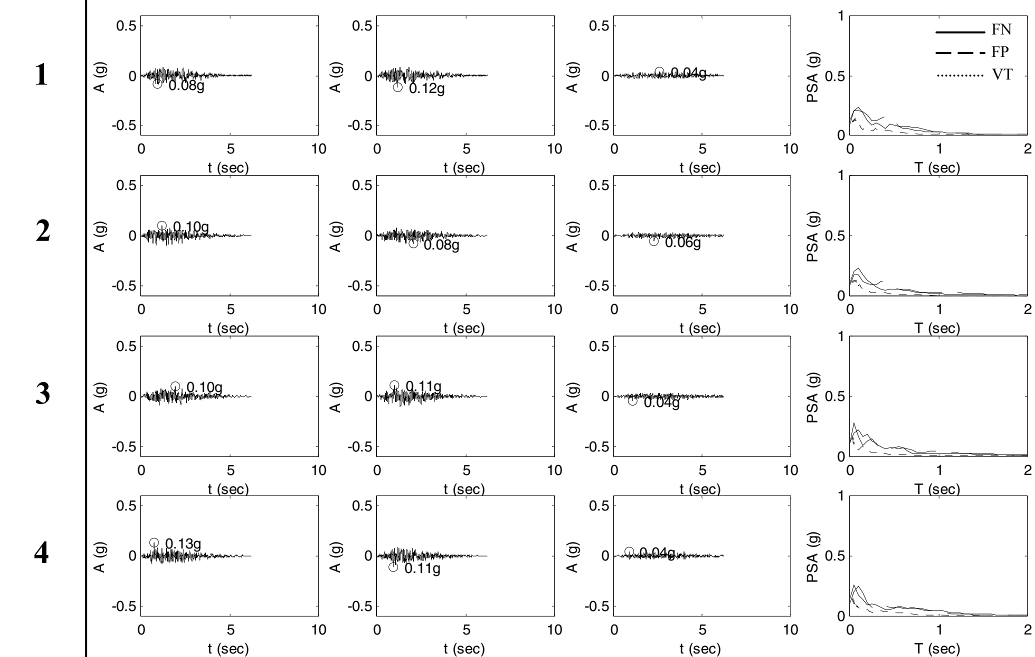


Figure B-1 New York : 2% Probability of Exceedance in 50 Years Short Ensemble (Cont'd)

Scenario 4 (5.8 M_w, 33.7 km)

Event No. | **Fault-Normal** | **Fault-Parallel** | **Vertical** | **PSA**



Scenario 5 (6.8 M_w, 36.2 km)

Event No. | **Fault-Normal** | **Fault-Parallel** | **Vertical** | **PSA**

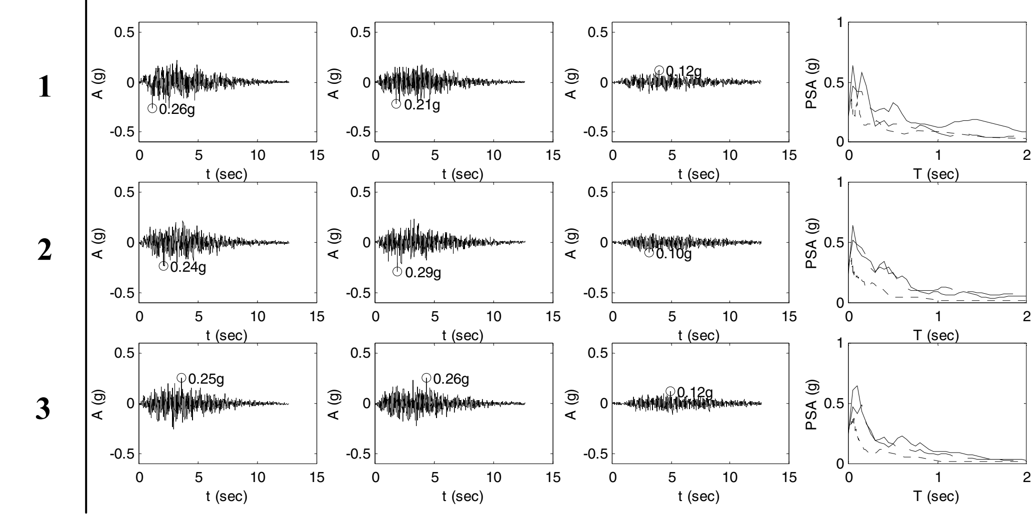
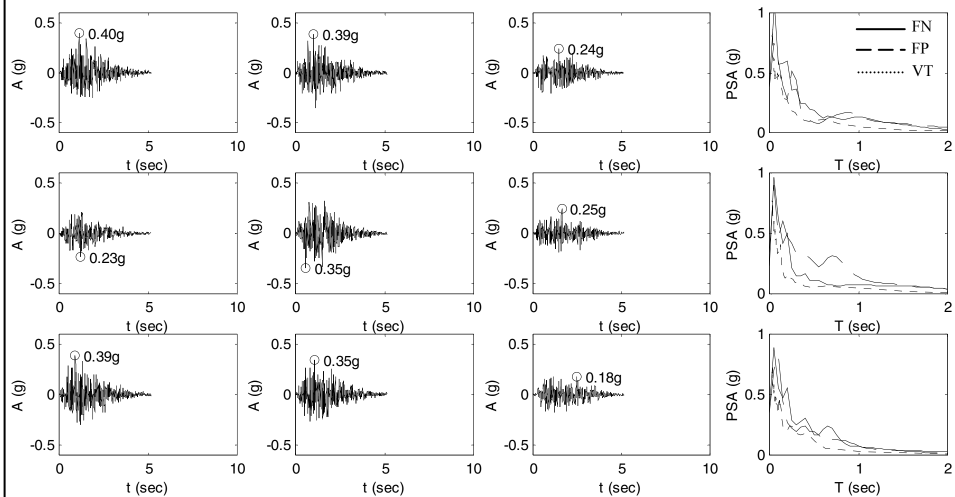


Figure B-1 New York : 2% Probability of Exceedance in 50 Years Short Ensemble (Cont'd)

Scenario 6 (6.0 M_w, 15.5 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				
2				
3				



Scenario 7 (6.0 M_w, 35.9 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				
2				
3				

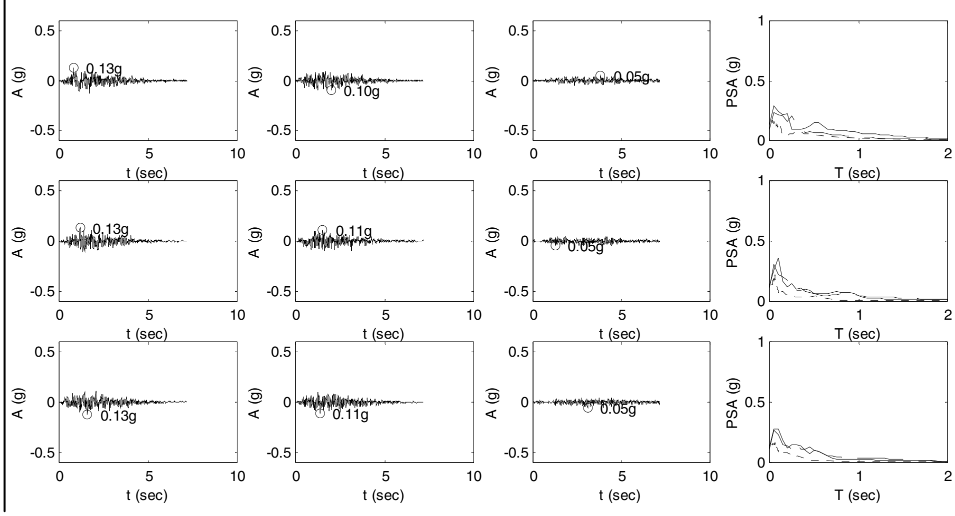
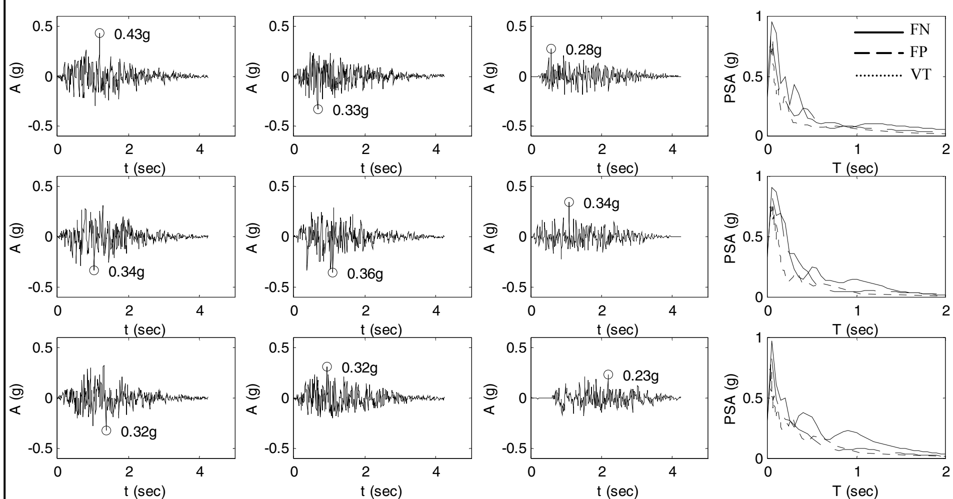


Figure B-1 New York : 2% Probability of Exceedance in 50 Years Short Ensemble (Cont'd)

Scenario 8 (5.8 M_w, 13.9 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				
2				
3				



Scenario 9 (6.4 M_w, 36.2 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				
2				
3				

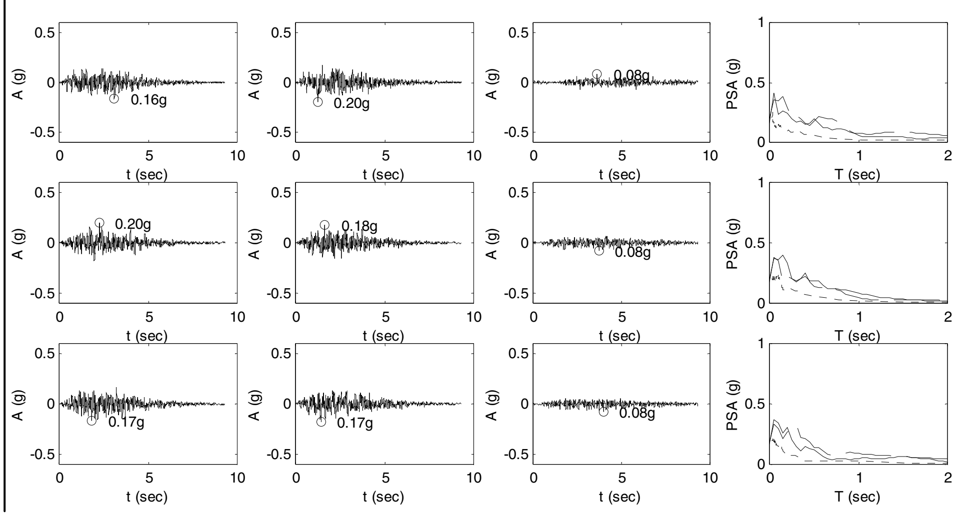
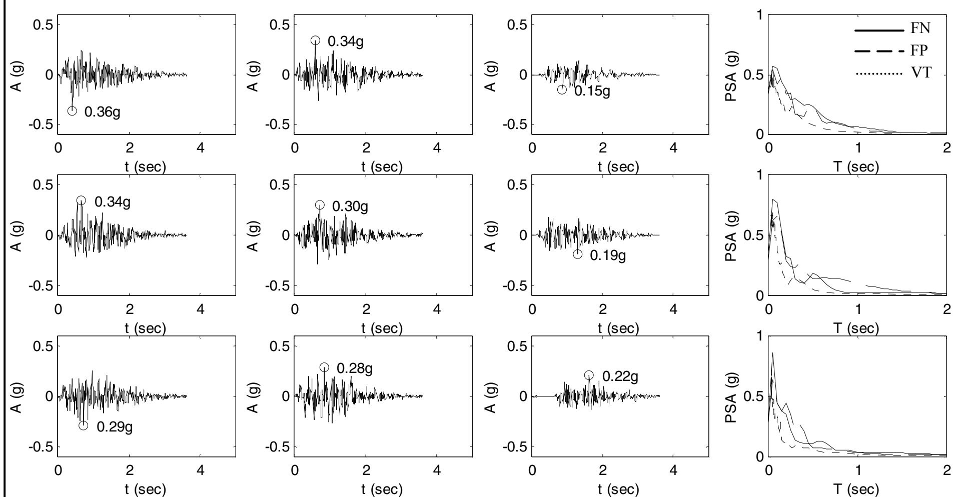


Figure B-1 New York : 2% Probability of Exceedance in 50 Years Short Ensemble (Cont'd)

Scenario 10 (5.6 M_w, 13.6 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				
2				
3				



Scenario 11 (5.6 M_w, 33.6 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				
2				

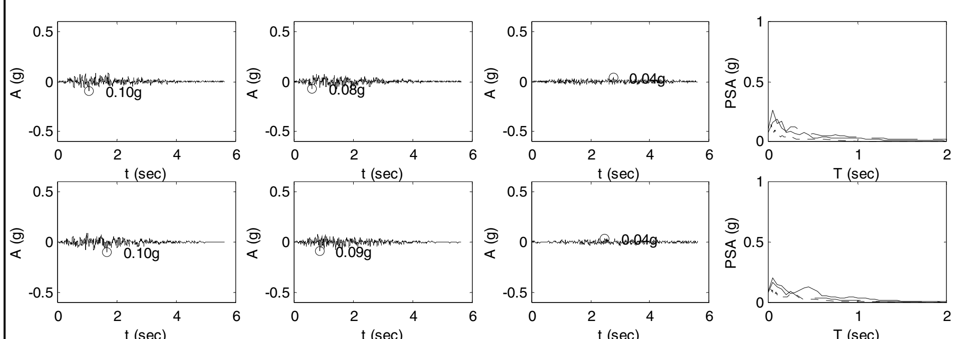


Figure B-1 New York : 2% Probability of Exceedance in 50 Years Short Ensemble (Cont'd)

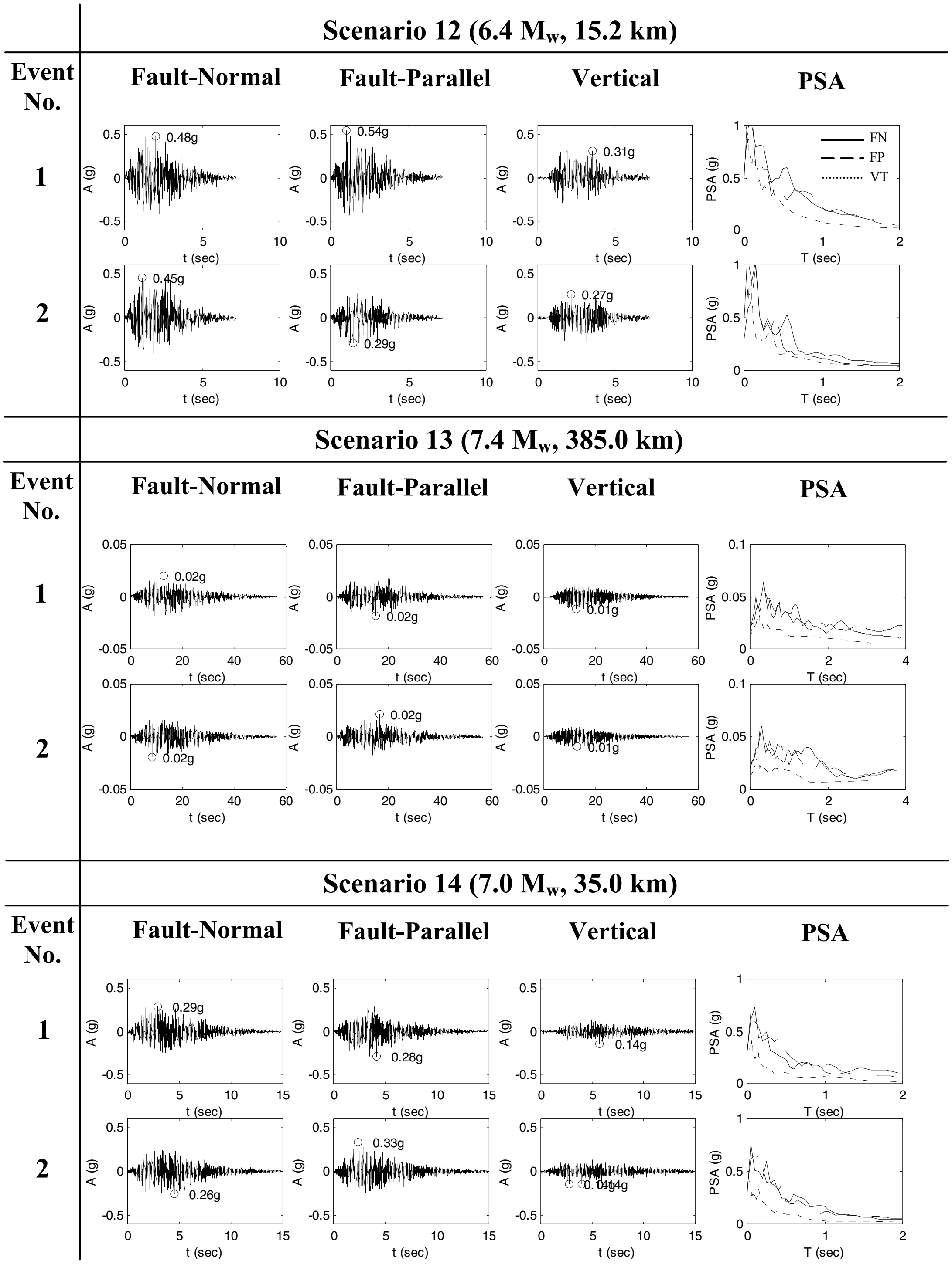


Figure B-1 New York : 2% Probability of Exceedance in 50 Years Short Ensemble (Cont'd)

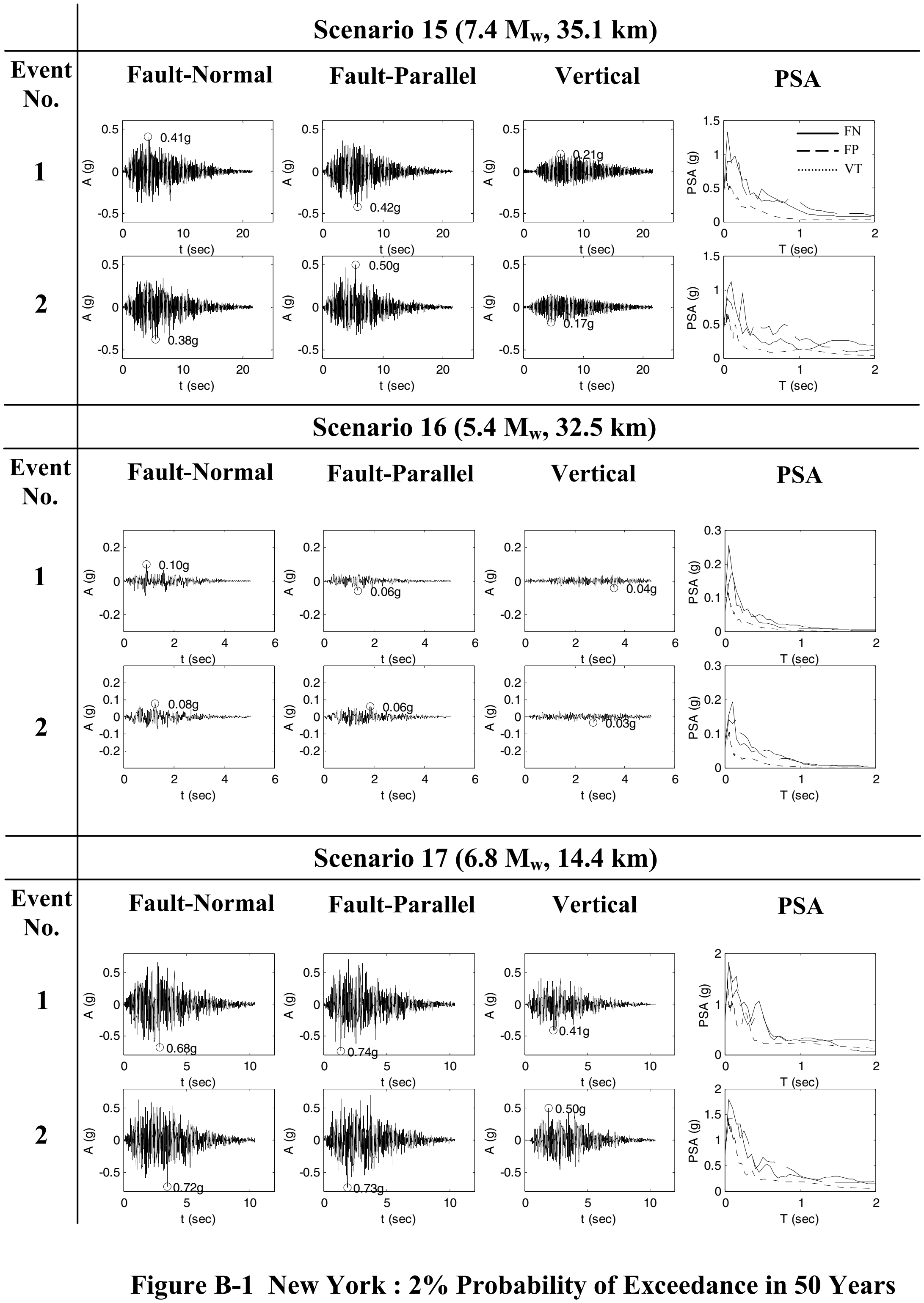


Figure B-1 New York : 2% Probability of Exceedance in 50 Years Short Ensemble (Cont'd)

Scenario 18 (5.0 M_w, 11.9 km)

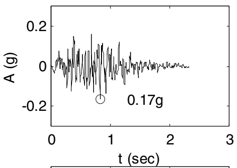
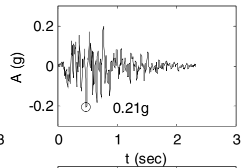
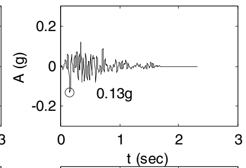
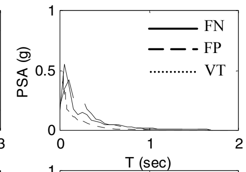
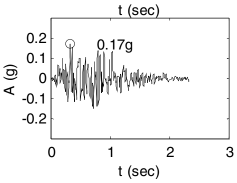
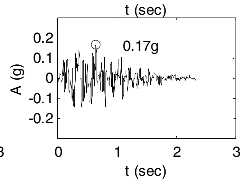
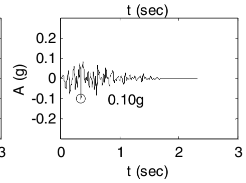
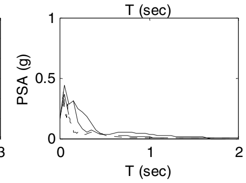
Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				
2				

Figure B-1 New York : 2% Probability of Exceedance in 50 Years Short Ensemble (Cont'd)

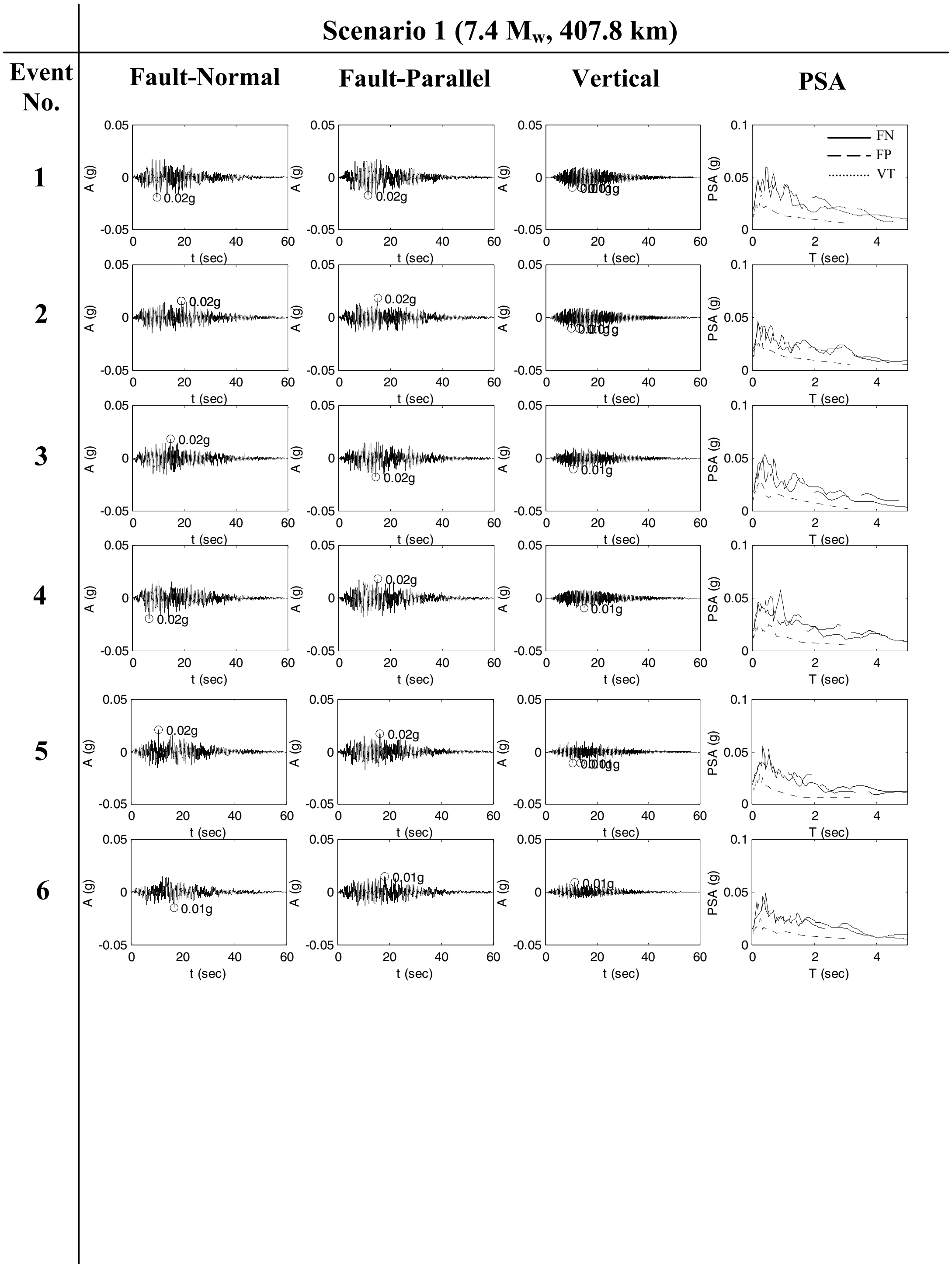


Figure B-2 New York : 5% Probability of Exceedance in 50 Years
Short Ensemble

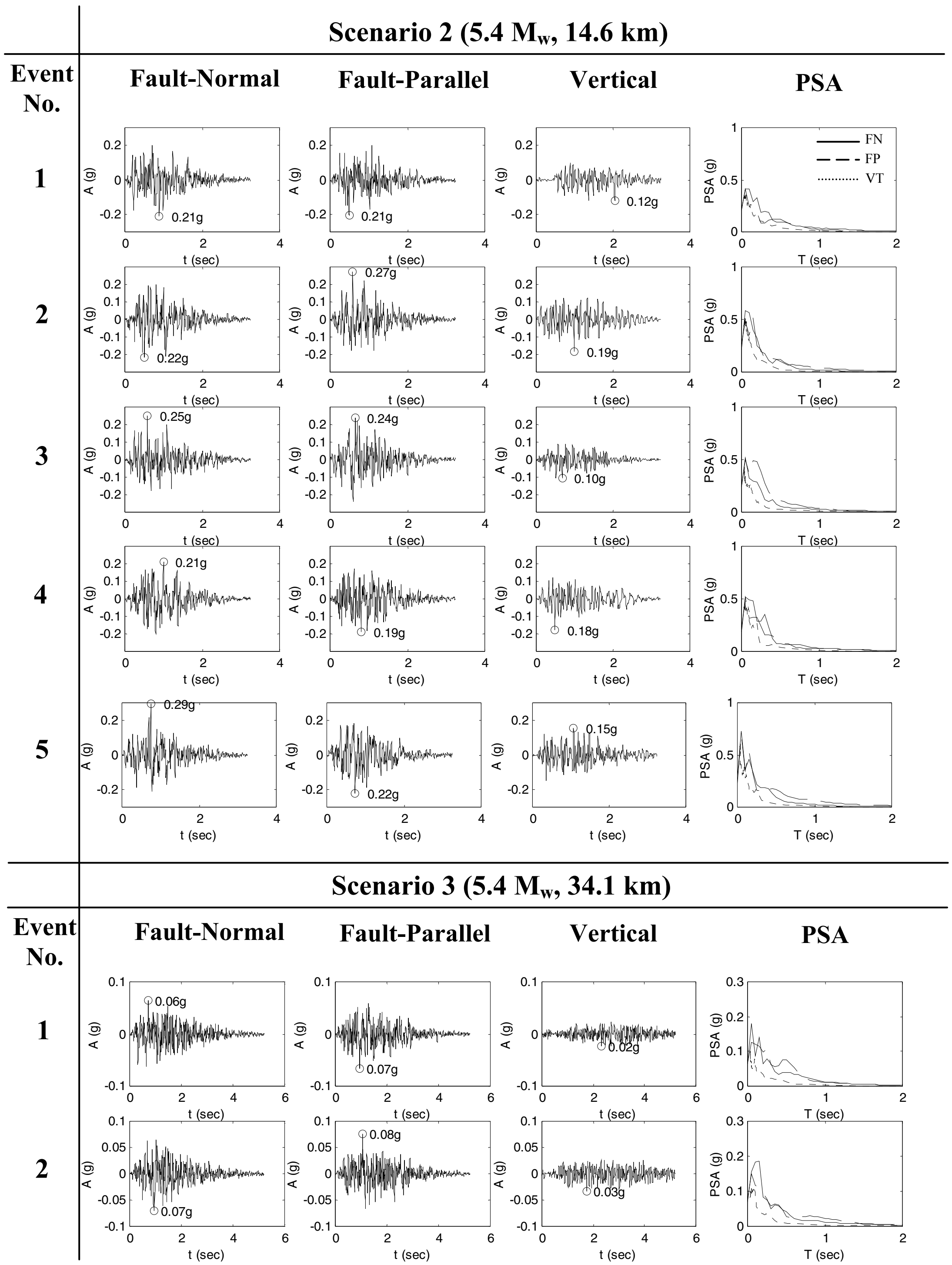


Figure B-2 New York : 5% Probability of Exceedance in 50 Years
Short Ensemble (Cont'd)

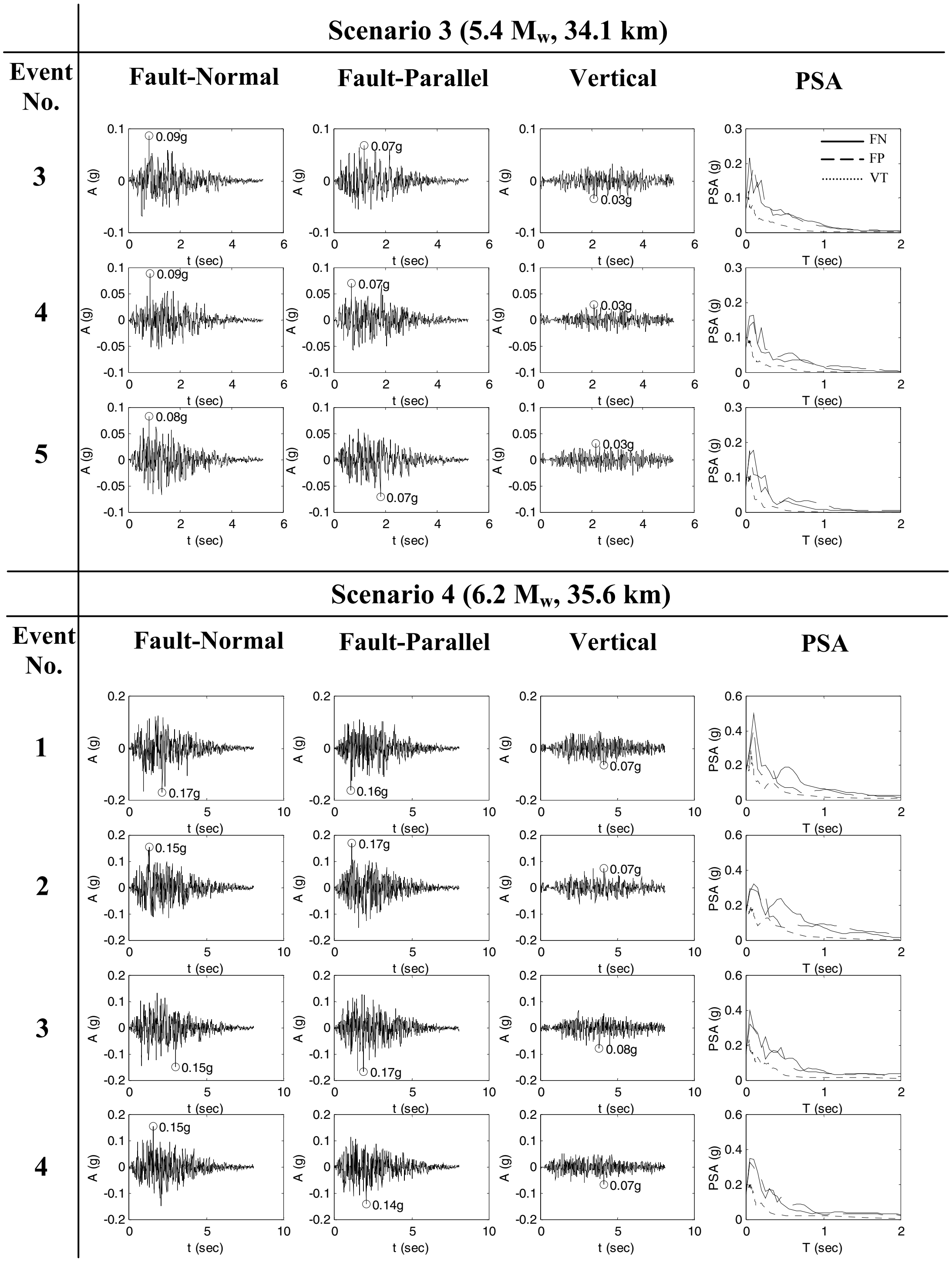


Figure B-2 New York : 5% Probability of Exceedance in 50 Years Short Ensemble (Cont'd)

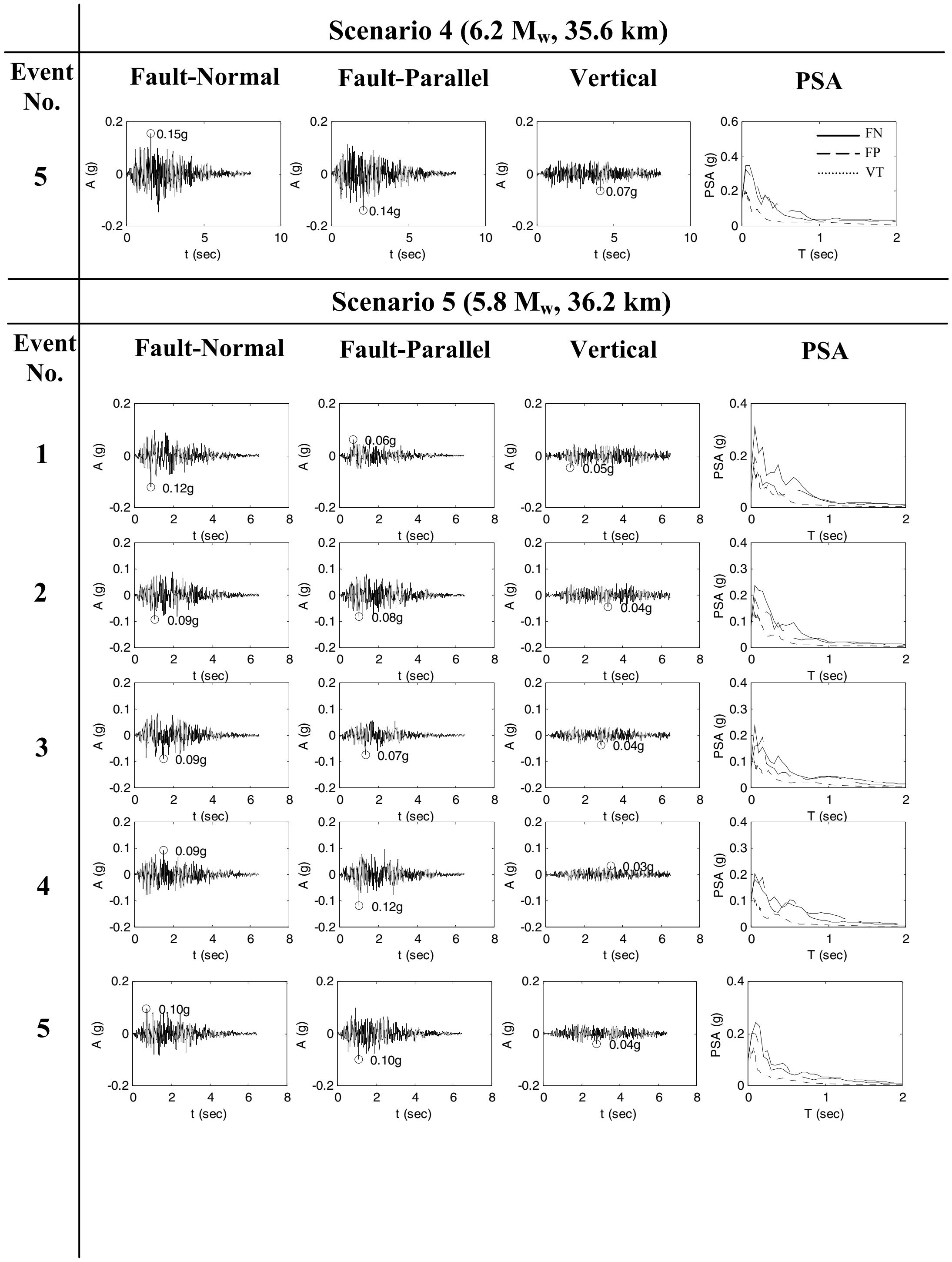


Figure B-2 New York : 5% Probability of Exceedance in 50 Years
Short Ensemble (Cont'd)

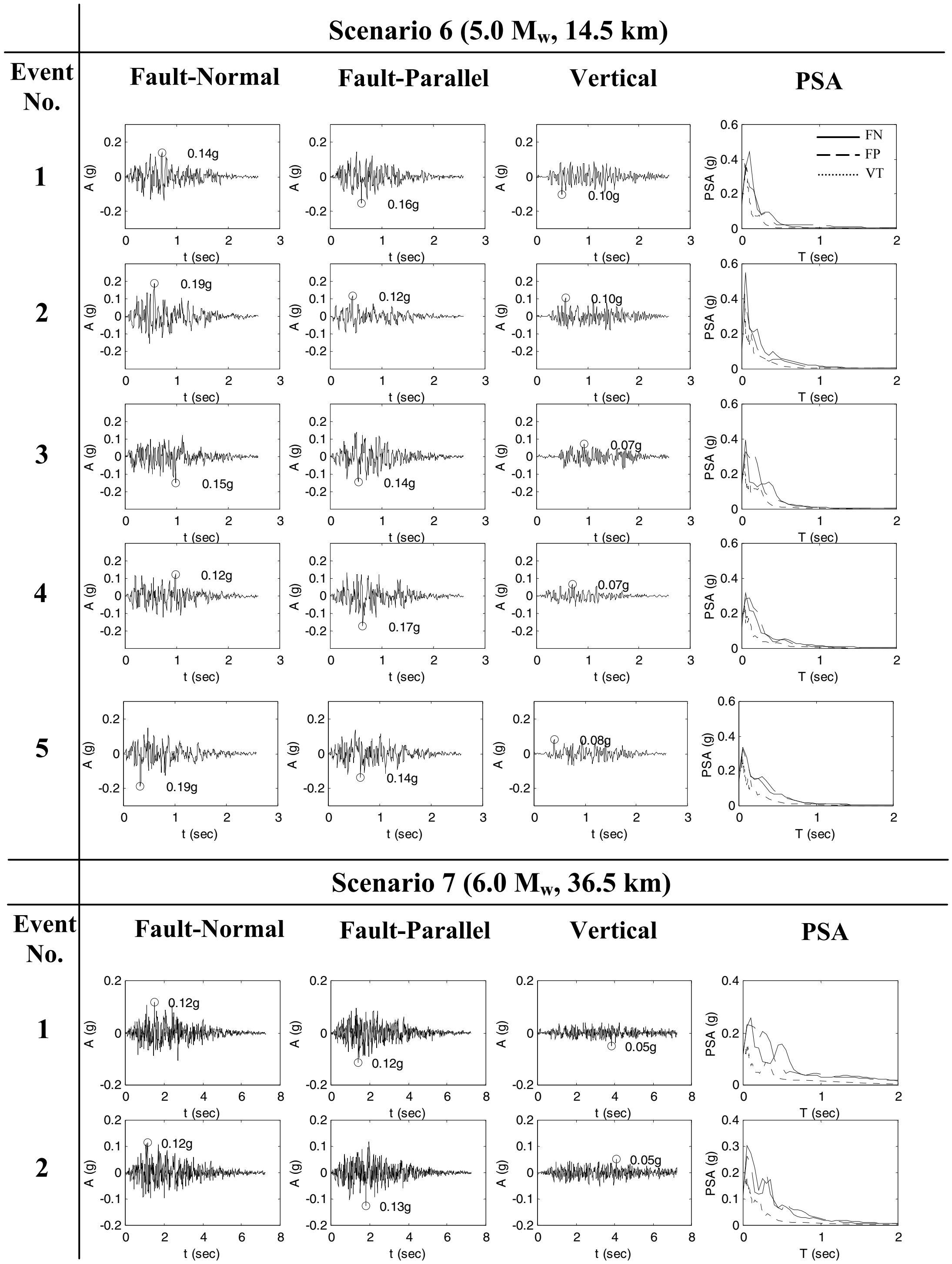


Figure B-2 New York : 5% Probability of Exceedance in 50 Years Short Ensemble (Cont'd)

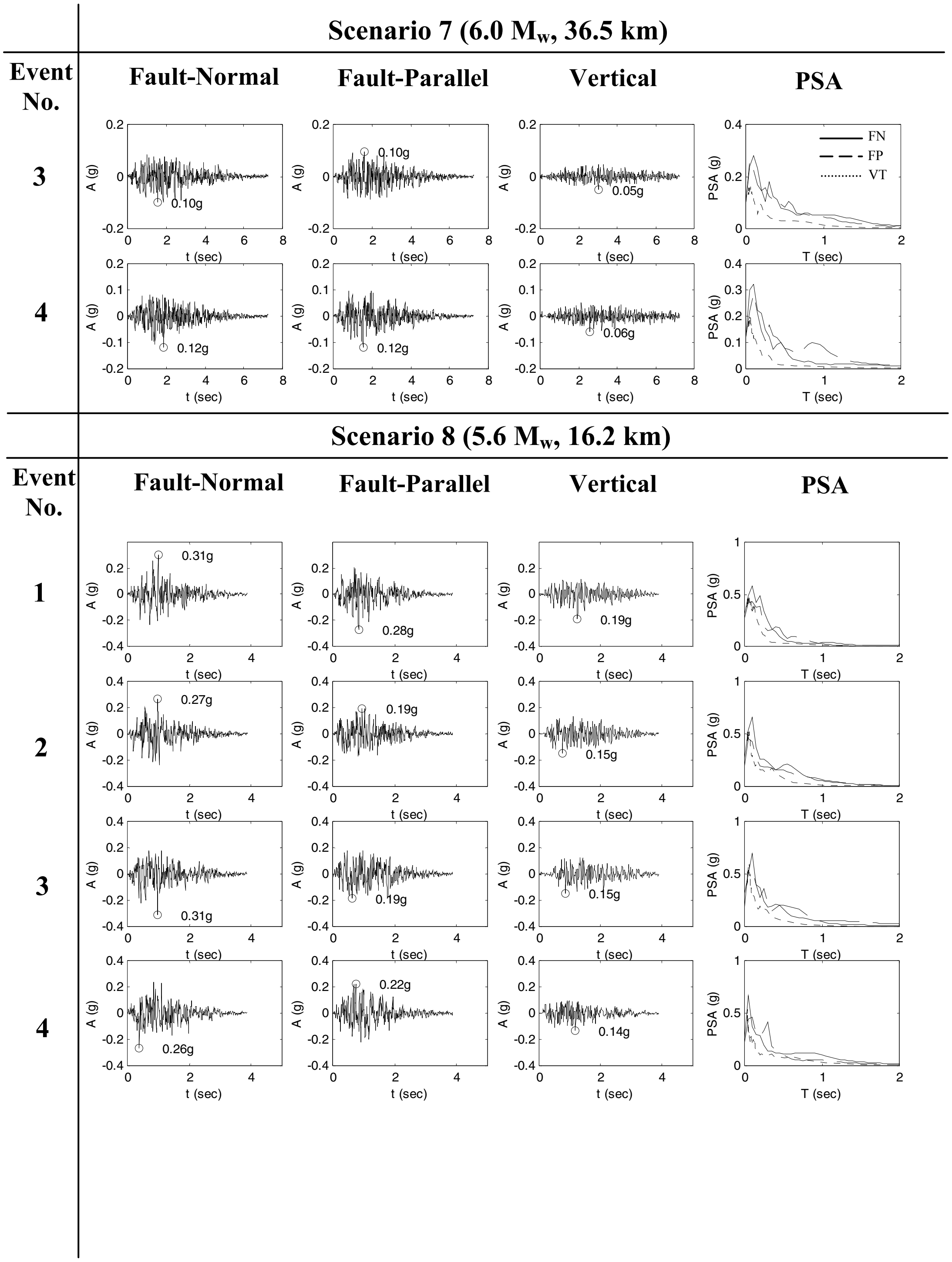


Figure B-2 New York : 5% Probability of Exceedance in 50 Years Short Ensemble (Cont'd)

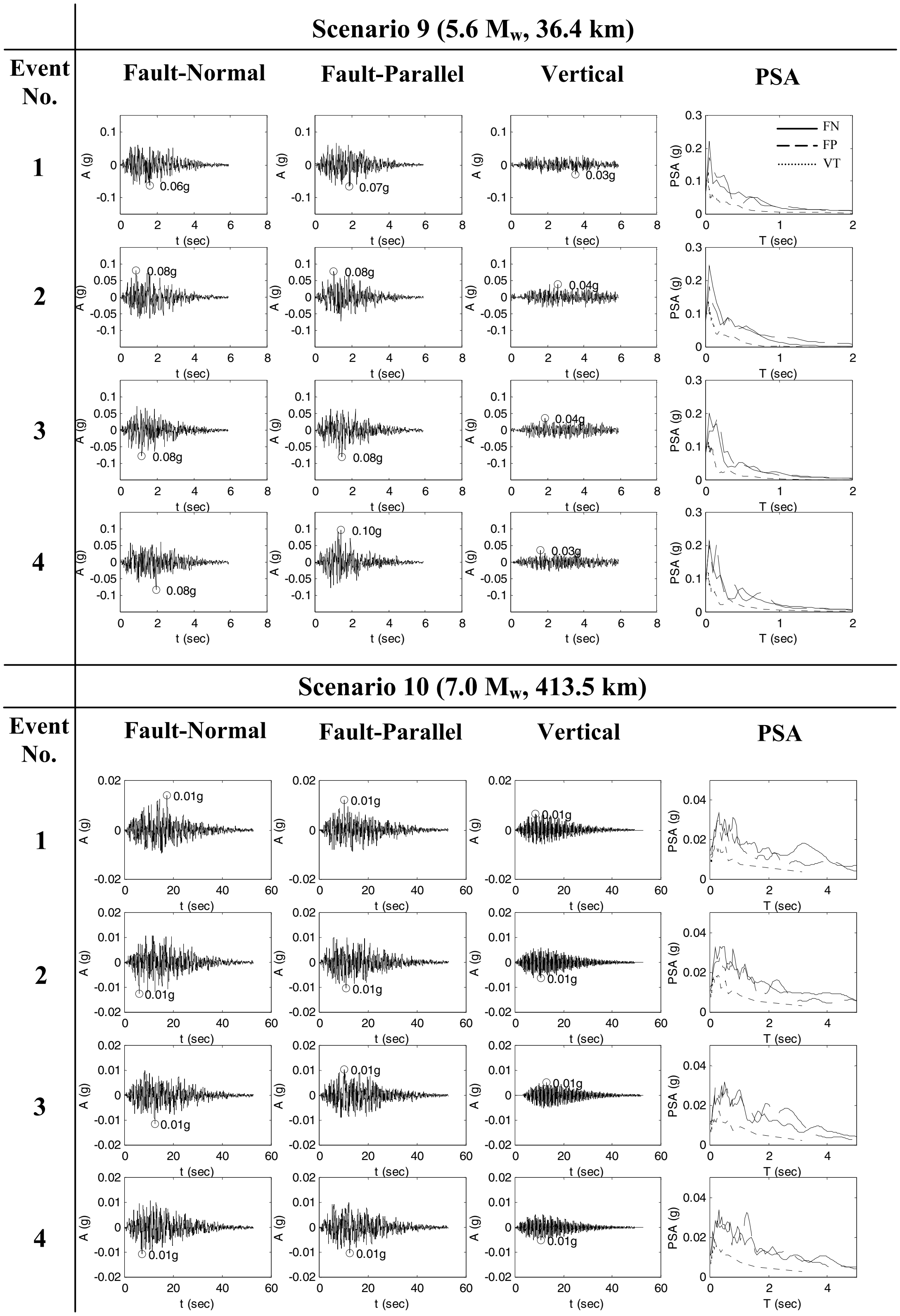


Figure B-2 New York : 5% Probability of Exceedance in 50 Years Short Ensemble (Cont'd)

Scenario 11 (5.8 M_w, 15.9 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				
2				
3				

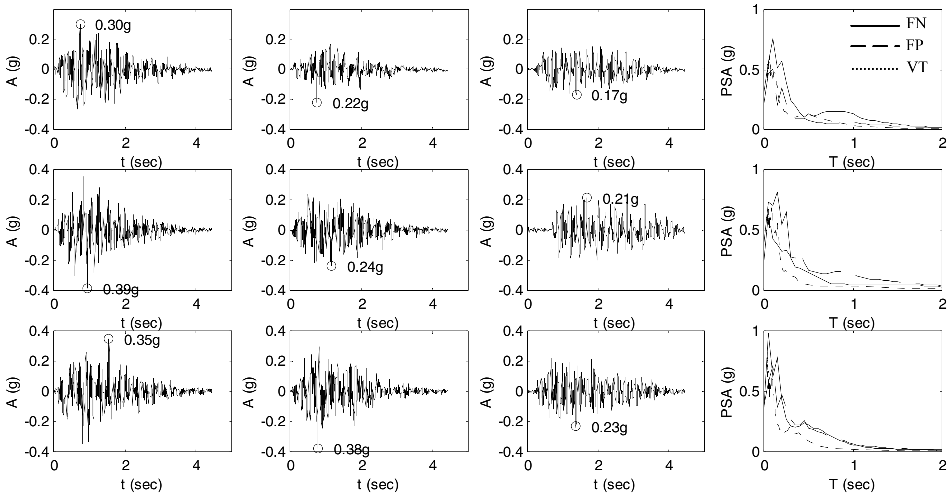


Figure B-2 New York : 5% Probability of Exceedance in 50 Years Short Ensemble (Cont'd)

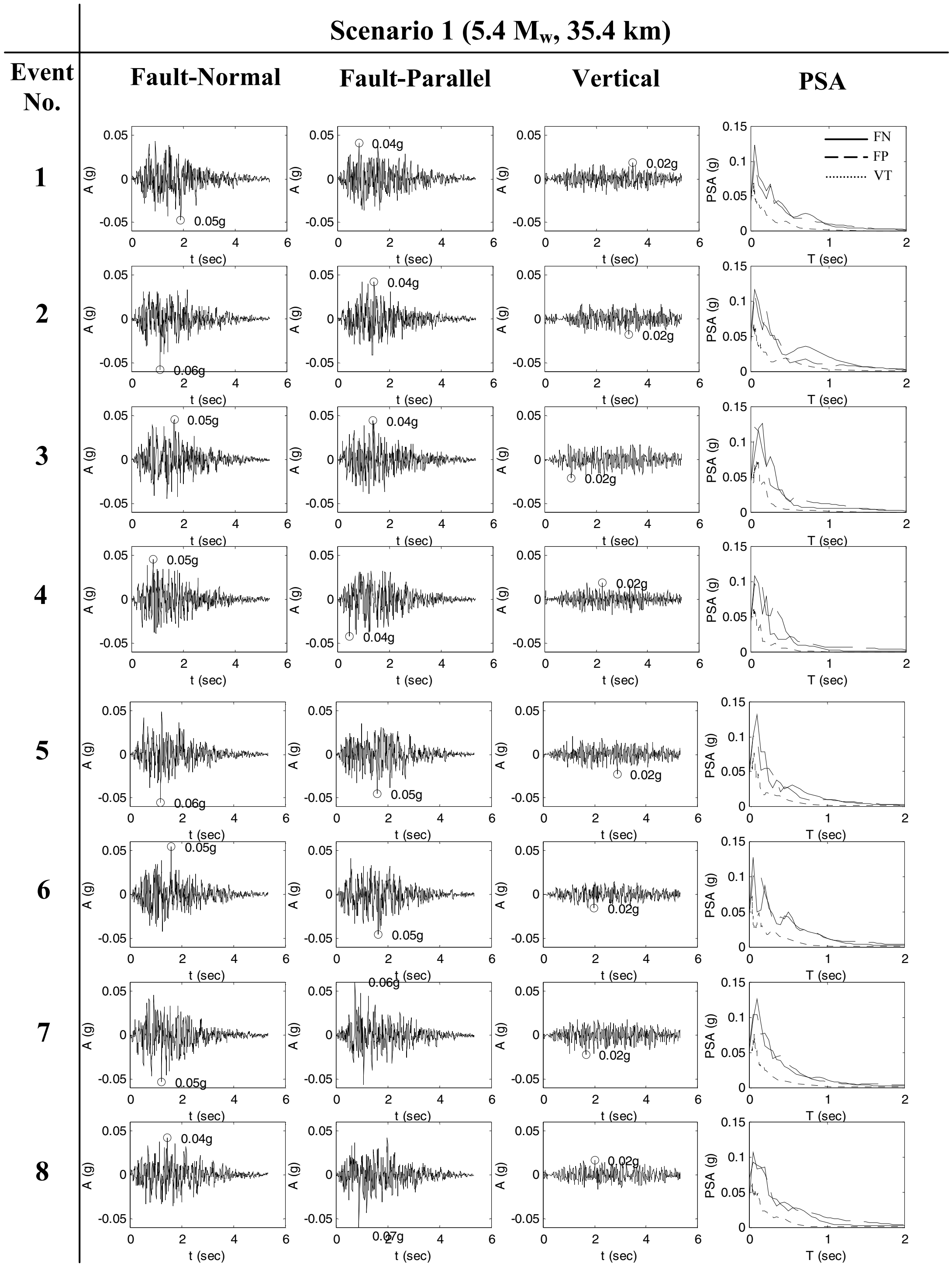


Figure B-3 New York : 10% Probability of Exceedance in 50 Years Short Ensemble

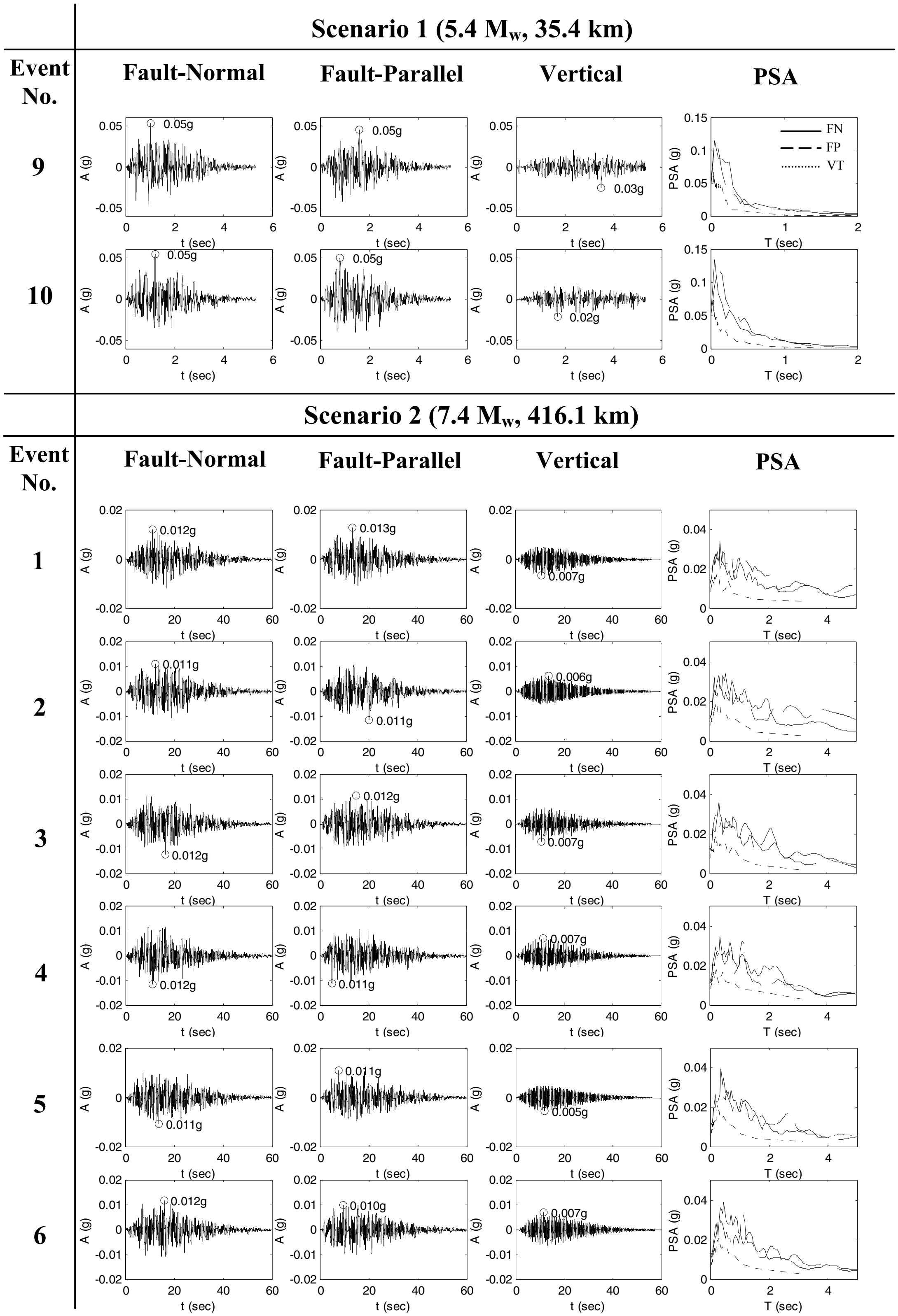


Figure B-3 New York : 10% Probability of Exceedance in 50 Years Short Ensemble (Cont'd)

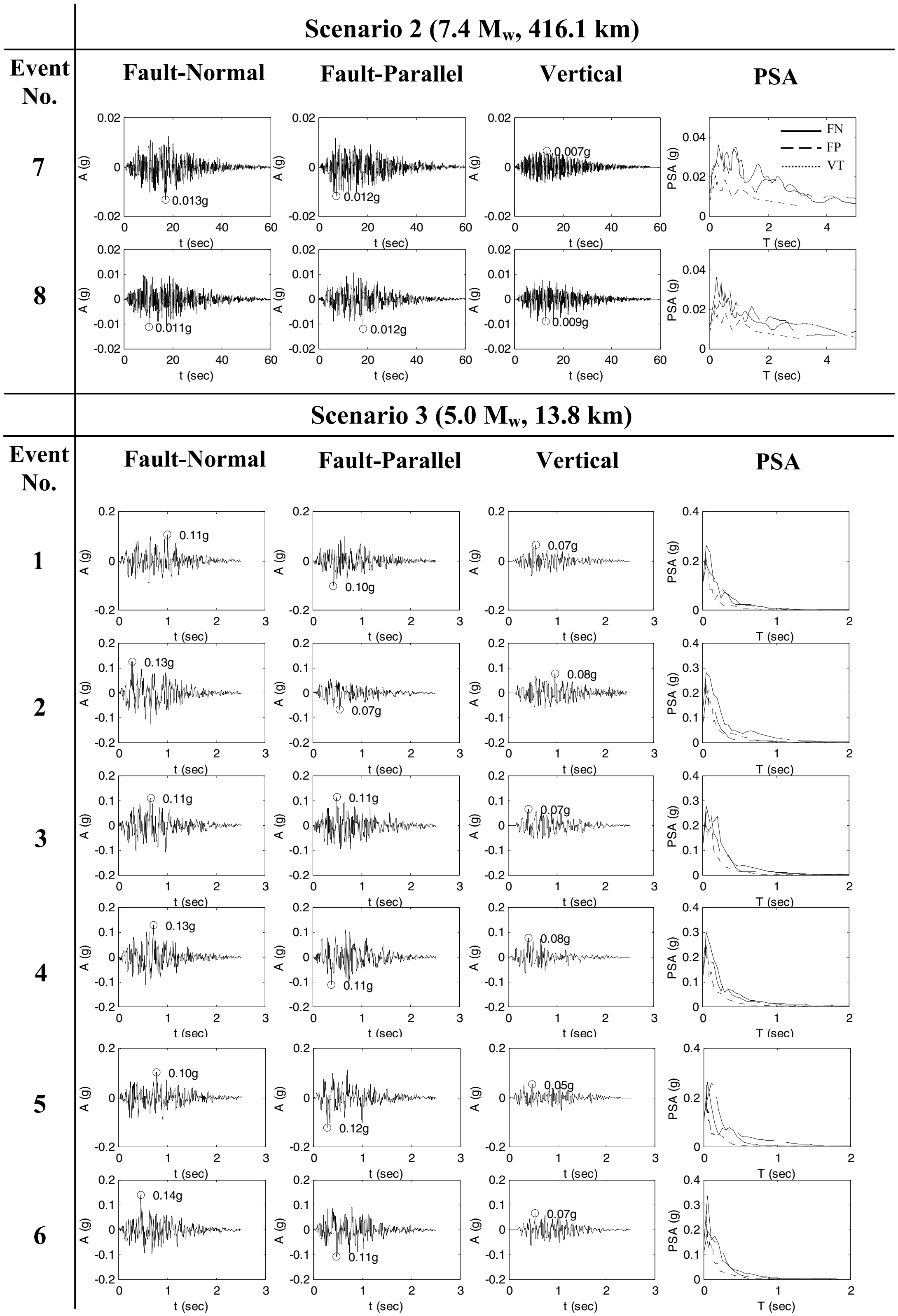


Figure B-3 New York : 10% Probability of Exceedance in 50 Years Short Ensemble (Cont'd)

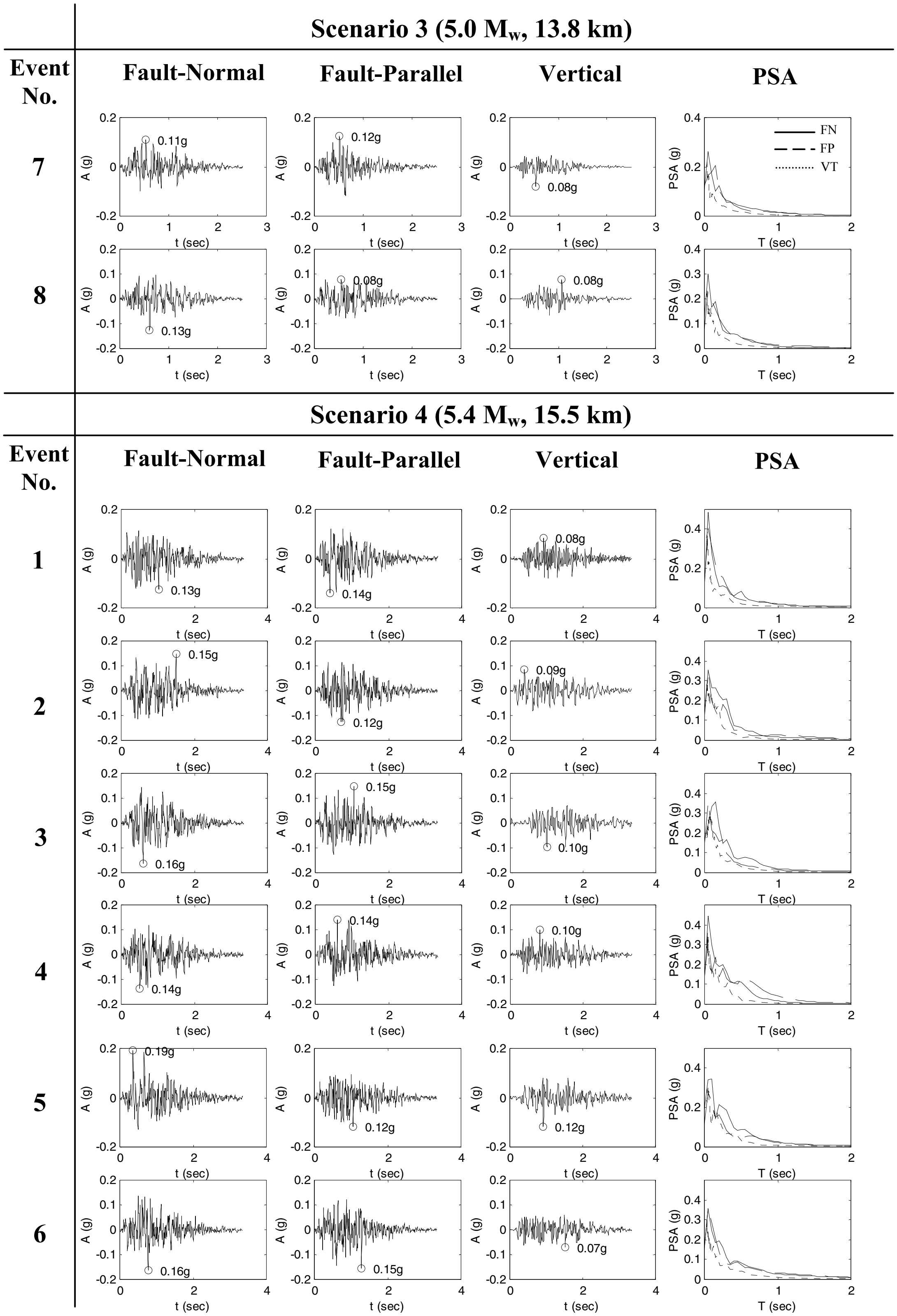


Figure B-3 New York : 10% Probability of Exceedance in 50 Years Short Ensemble (Cont'd)

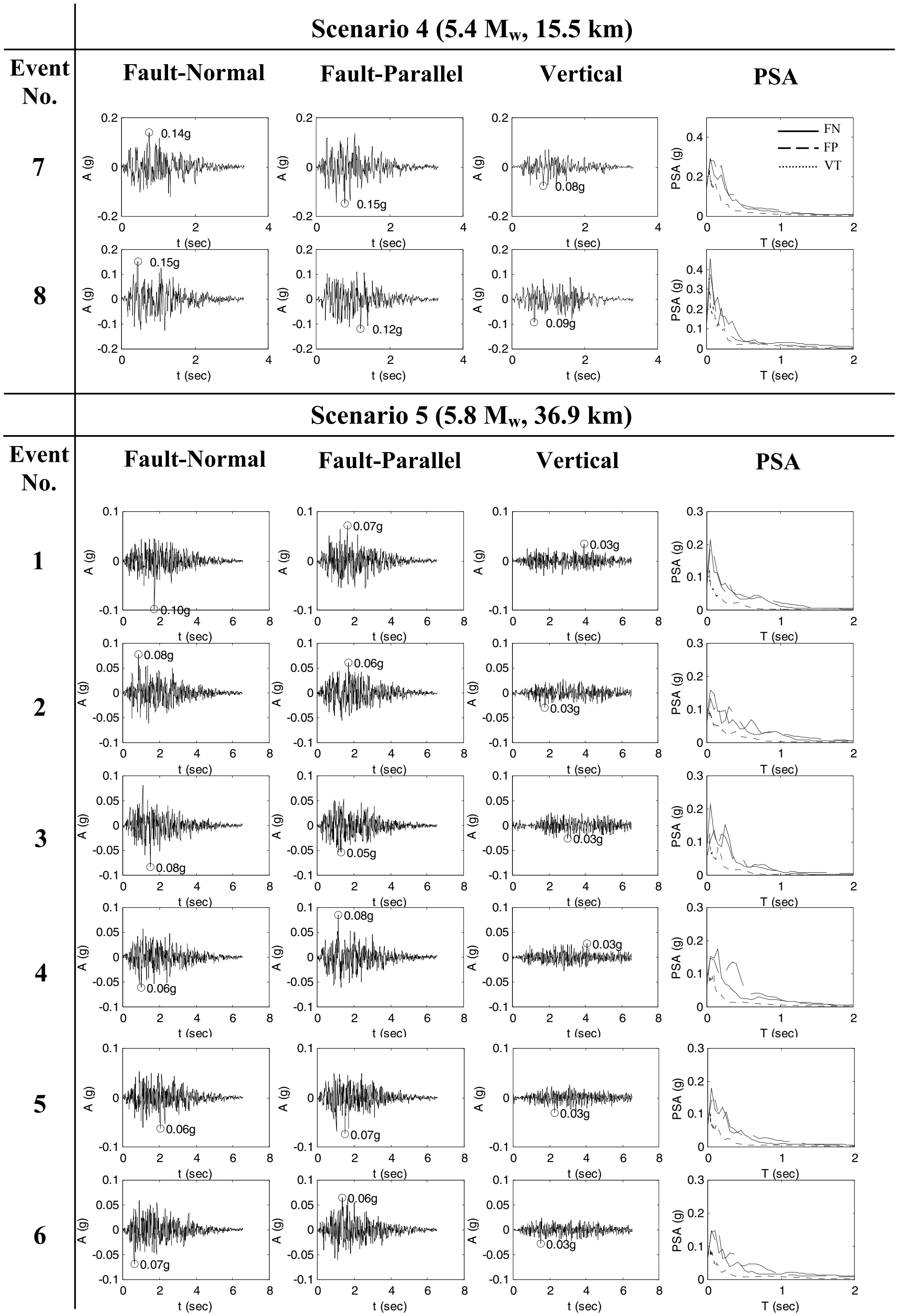


Figure B-3 New York : 10% Probability of Exceedance in 50 Years Short Ensemble (Cont'd)

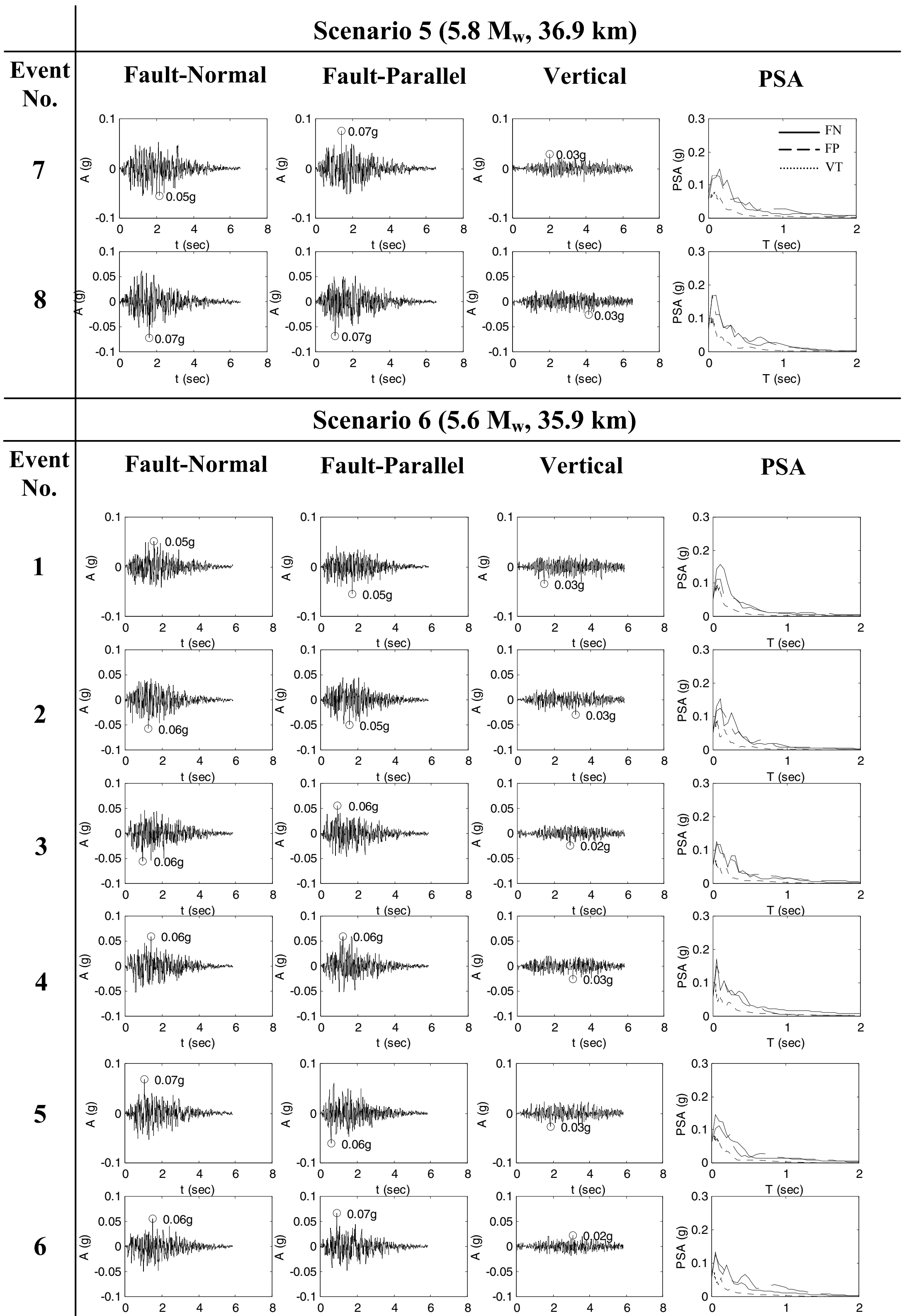


Figure B-3 New York : 10% Probability of Exceedance in 50 Years Short Ensemble (Cont'd)

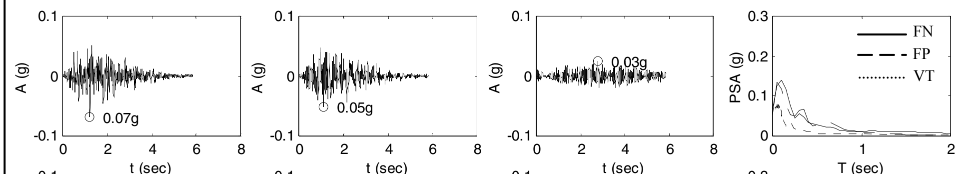
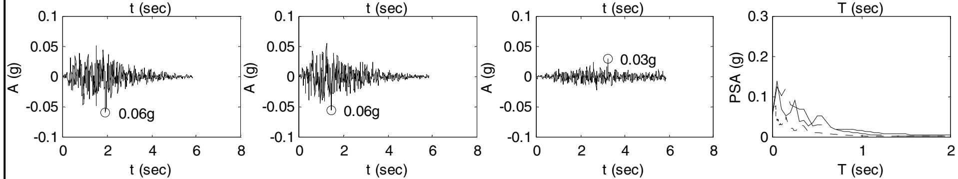
	Scenario 6 (5.6 M_w, 35.9 km)
Event No.	**Fault-Normal** **Fault-Parallel** **Vertical** **PSA**
7	
8	

Figure B-3 New York : 10% Probability of Exceedance in 50 Years Short Ensemble (Cont'd)

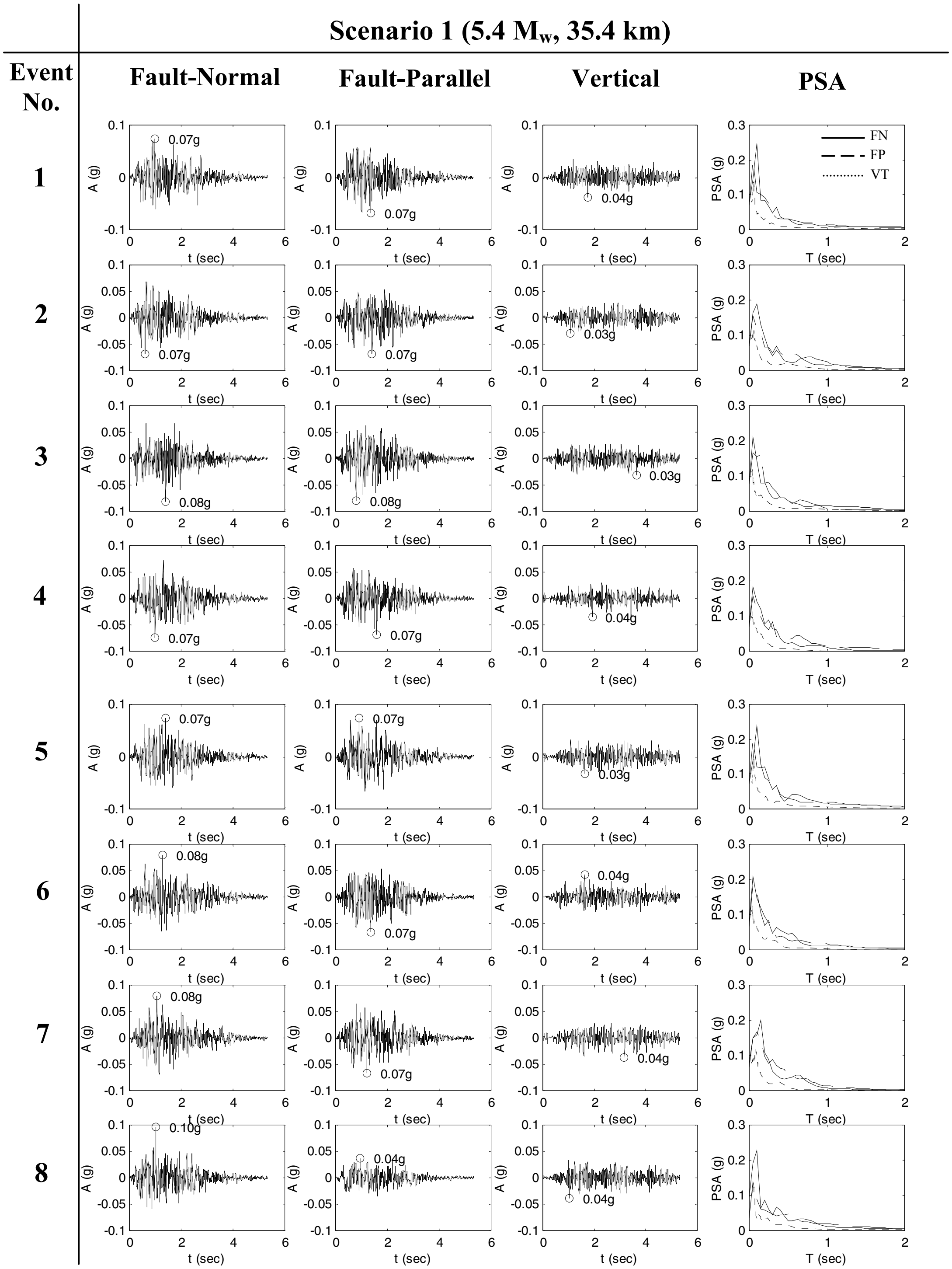


Figure B-4 New York : 20% Probability of Exceedance in 50 Years Short Ensemble

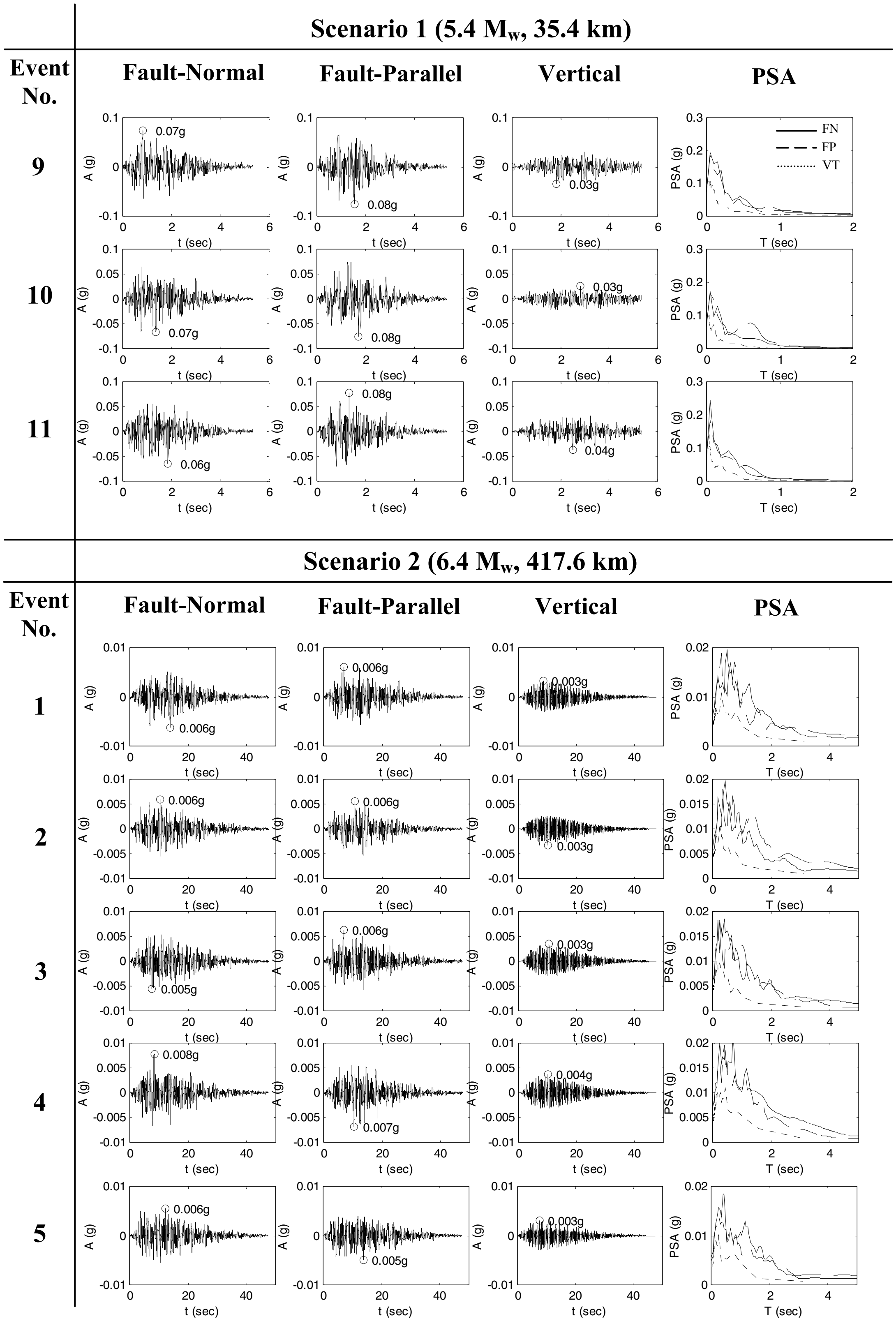


Figure B-4 New York : 20% Probability of Exceedance in 50 Years Short Ensemble (Cont'd)

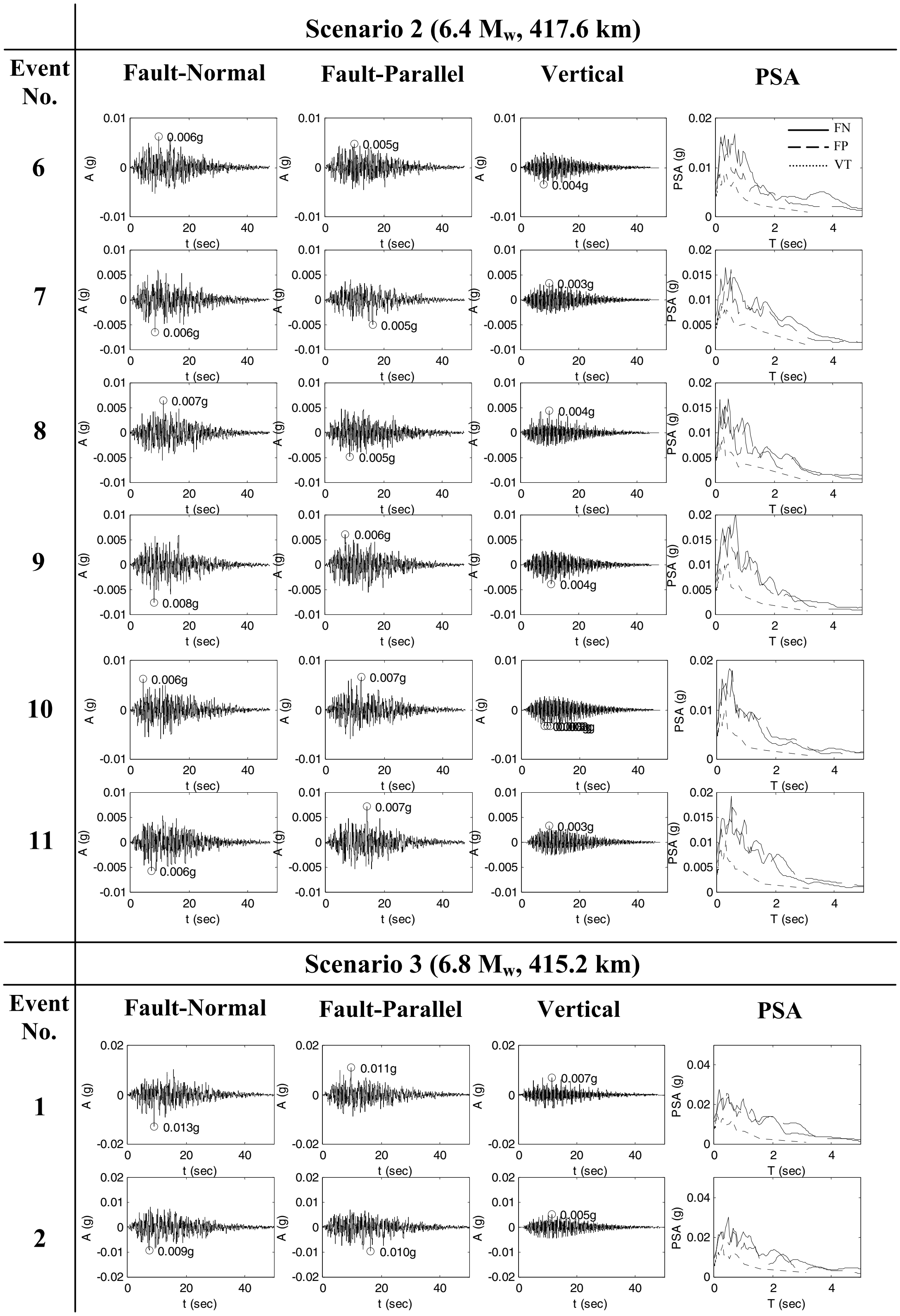


Figure B-4 New York : 20% Probability of Exceedance in 50 Years Short Ensemble (Cont'd)

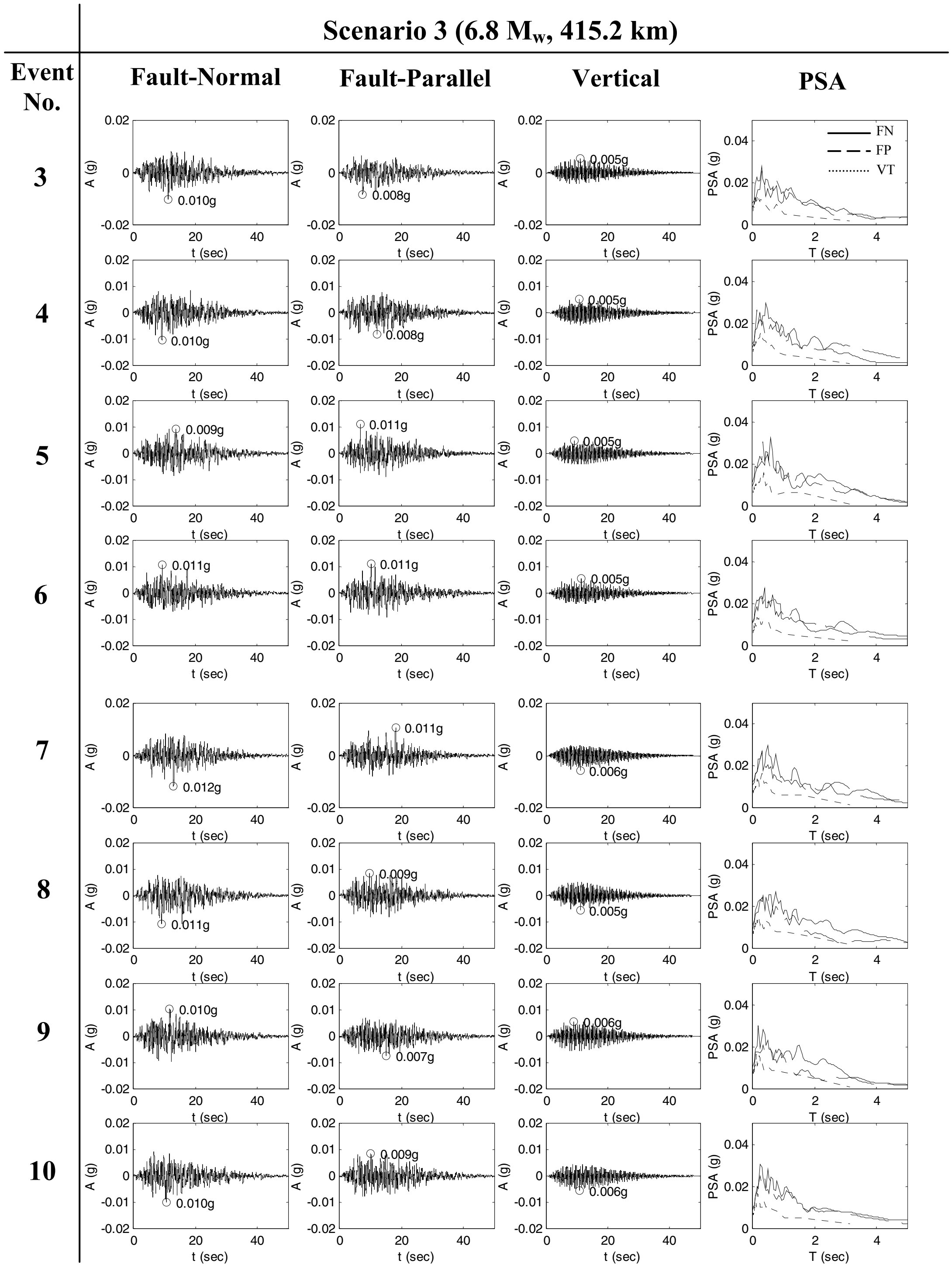


Figure B-4 New York : 20% Probability of Exceedance in 50 Years Short Ensemble (Cont'd)

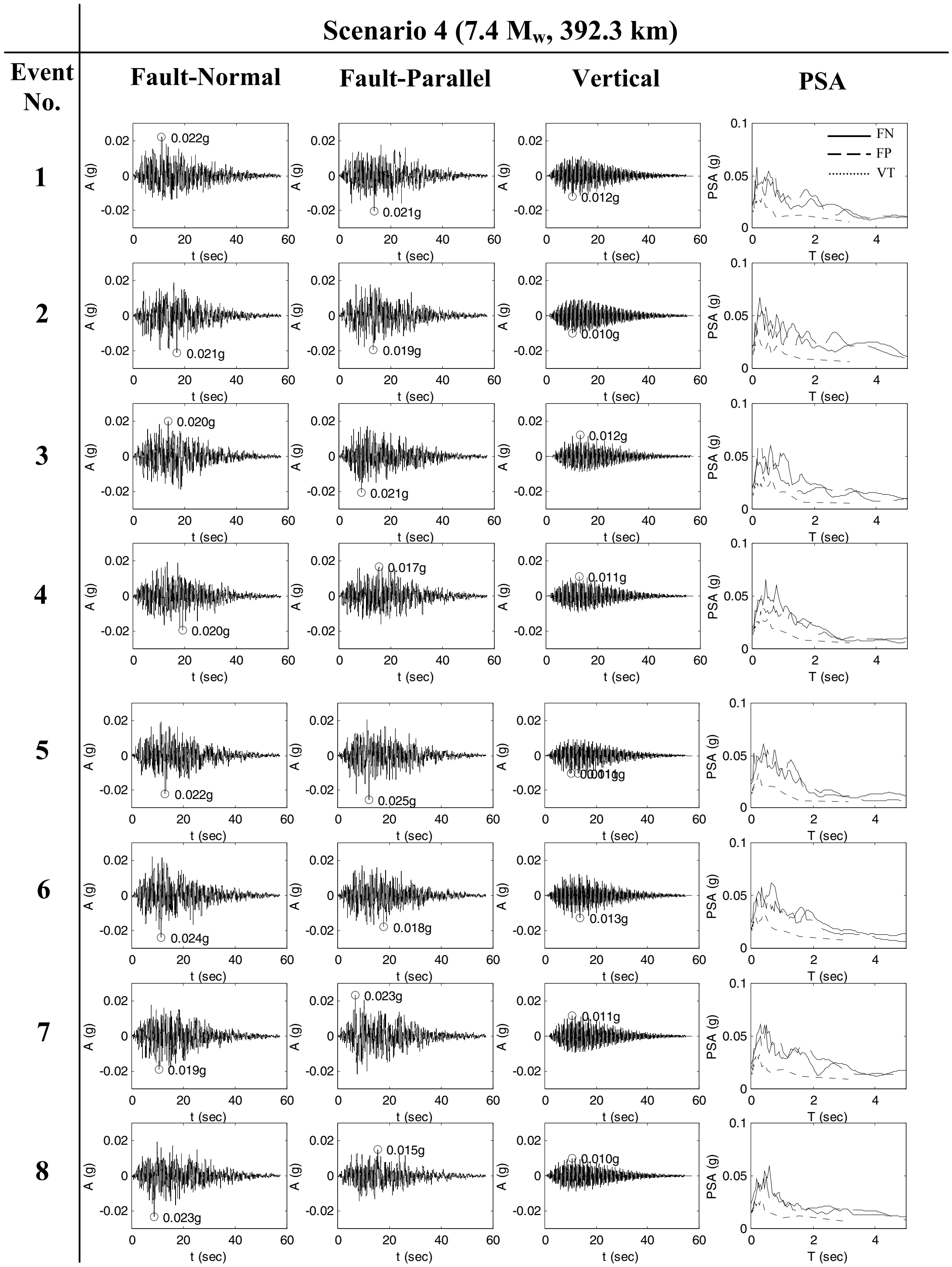


Figure B-4 New York : 20% Probability of Exceedance in 50 Years Short Ensemble (Cont'd)

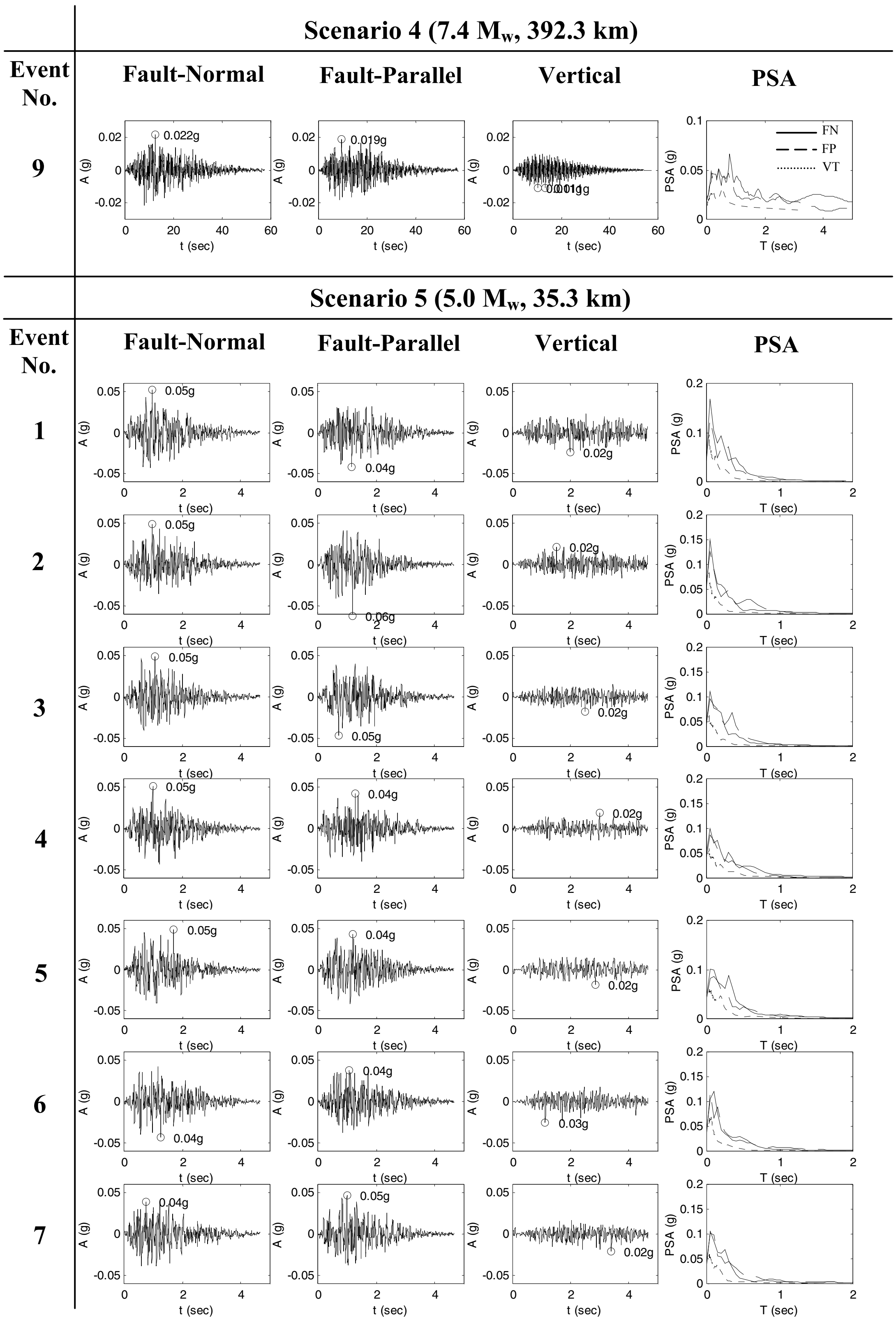


Figure B-4 New York : 20% Probability of Exceedance in 50 Years Short Ensemble (Cont'd)

Scenario 5 (5.0 M_w, 35.3 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA

8

9

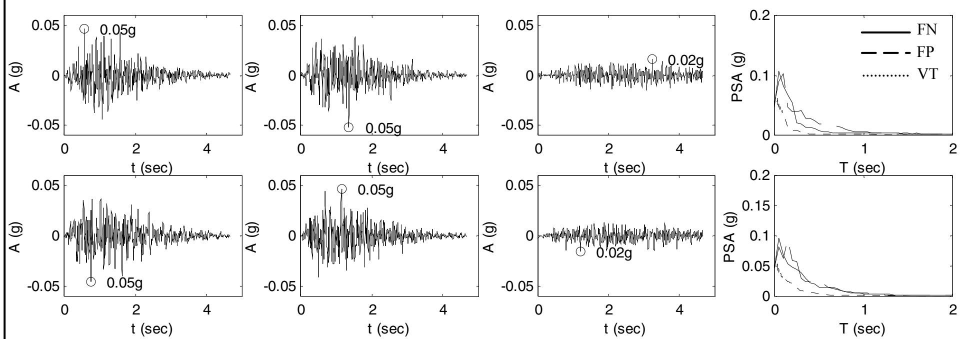


Figure B-4 New York : 20% Probability of Exceedance in 50 Years Short Ensemble (Cont'd)

APPENDIX C
EAST-COAST ACCELEROGRAMS AND RESPONSE SPECTRA
(LONG ENSEMBLE)

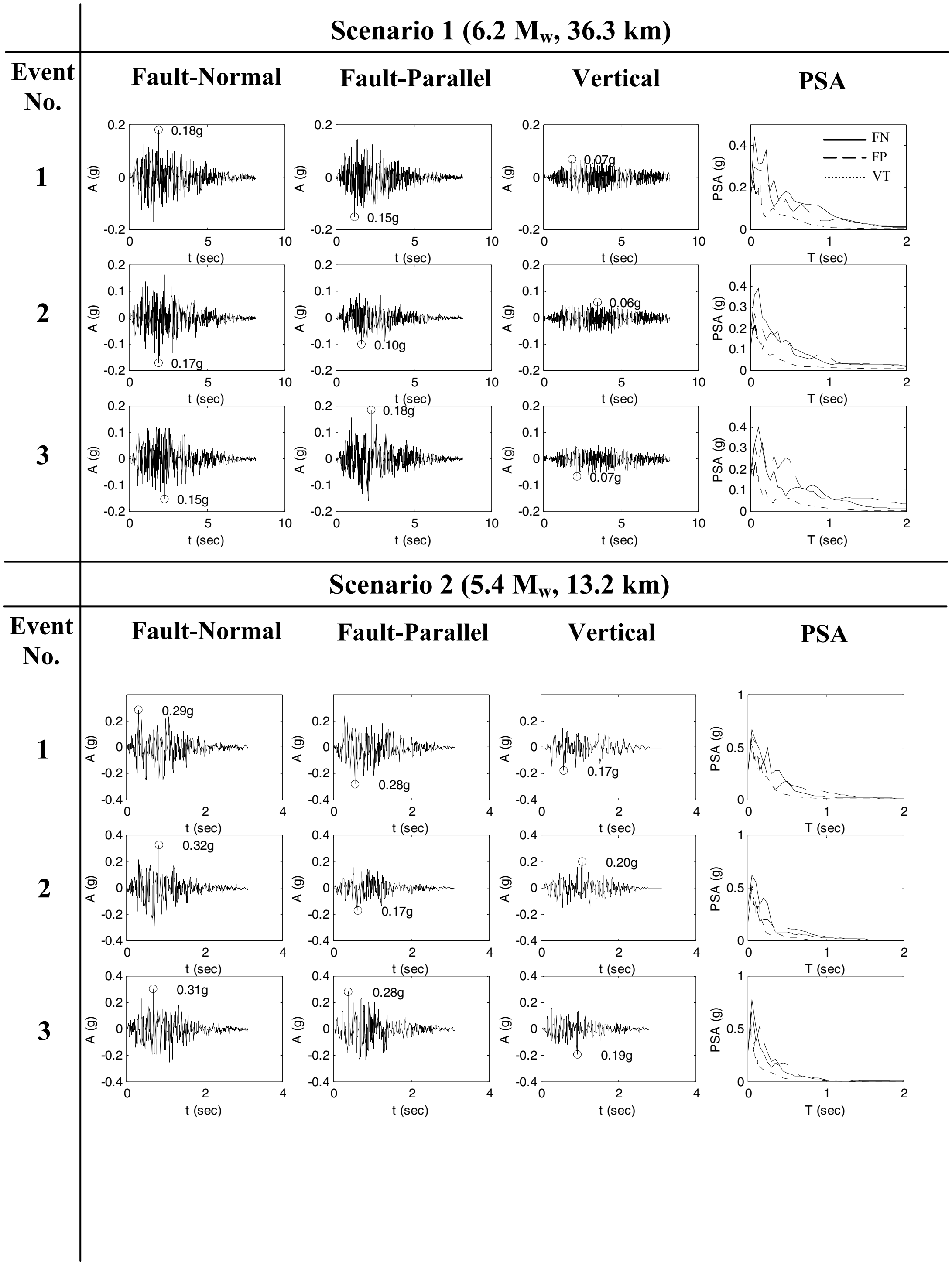
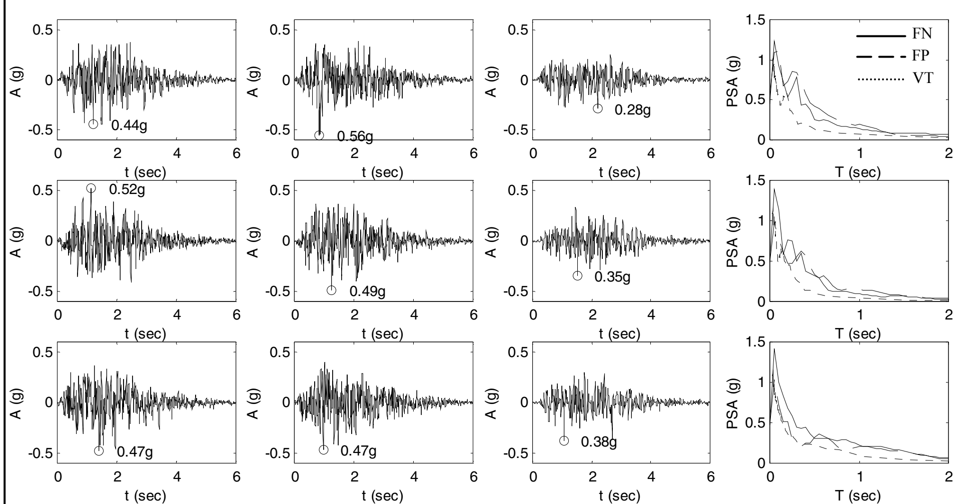


Figure C-1 New York : 2% Probability of Exceedance in 50 Years Long Ensemble

Scenario 3 (6.2 M_w, 15.6 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA

Event No.: 1, 2, 3



Scenario 4 (5.8 M_w, 33.7 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA

Event No.: 1, 2, 3

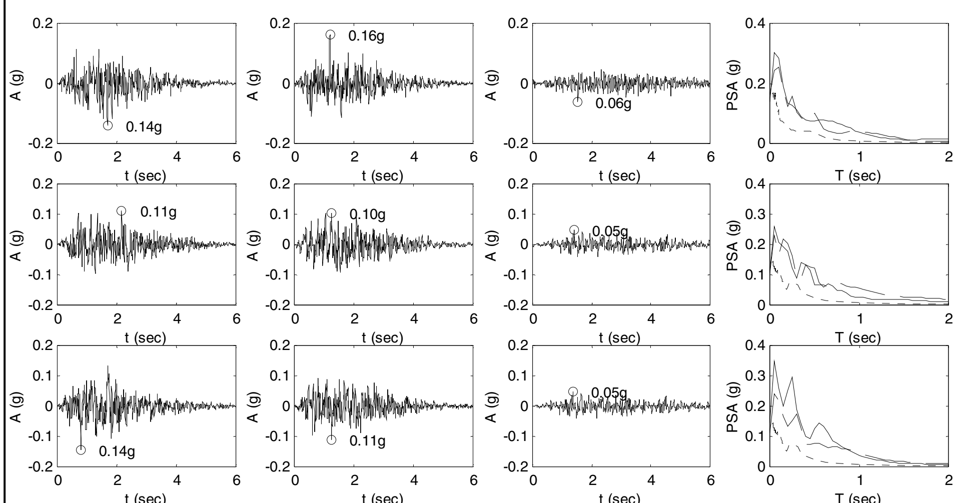


Figure C-1 New York : 2% Probability of Exceedance in 50 Years Long Ensemble (Cont'd)

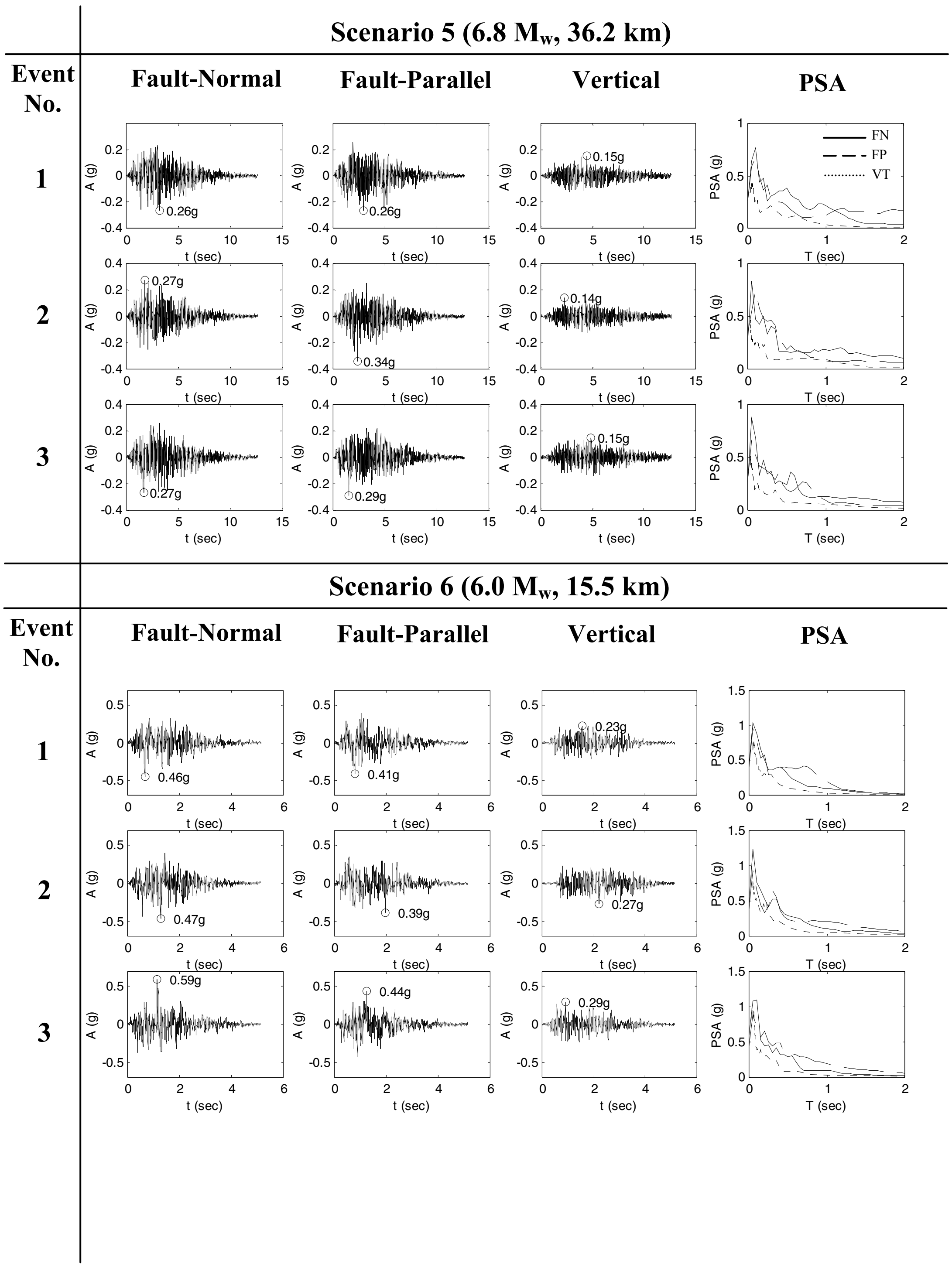


Figure C-1 New York : 2% Probability of Exceedance in 50 Years Long Ensemble (Cont'd)

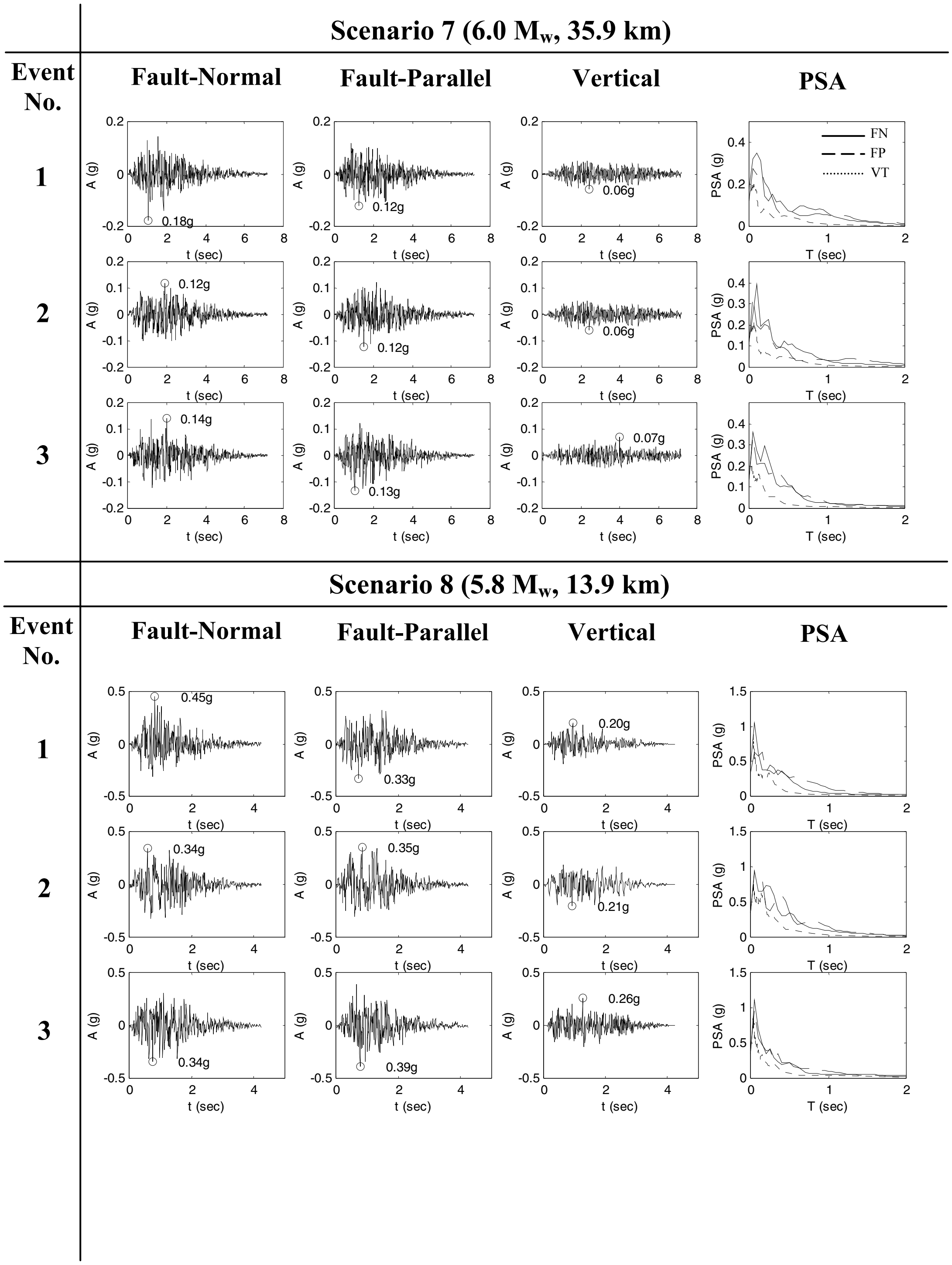
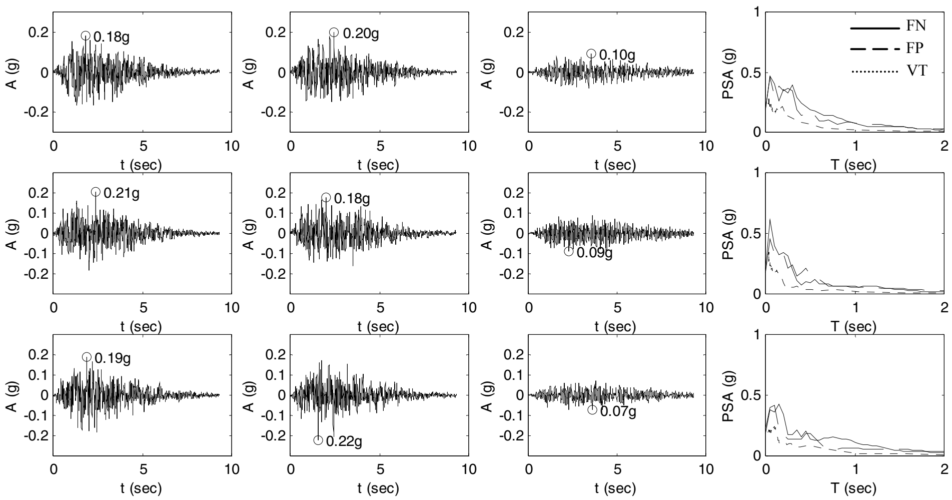


Figure C-1 New York : 2% Probability of Exceedance in 50 Years Long Ensemble (Cont'd)

Scenario 9 (6.4 M_w, 36.2 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				
2				
3				



Scenario 10 (5.6 M_w, 13.6 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				
2				
3				

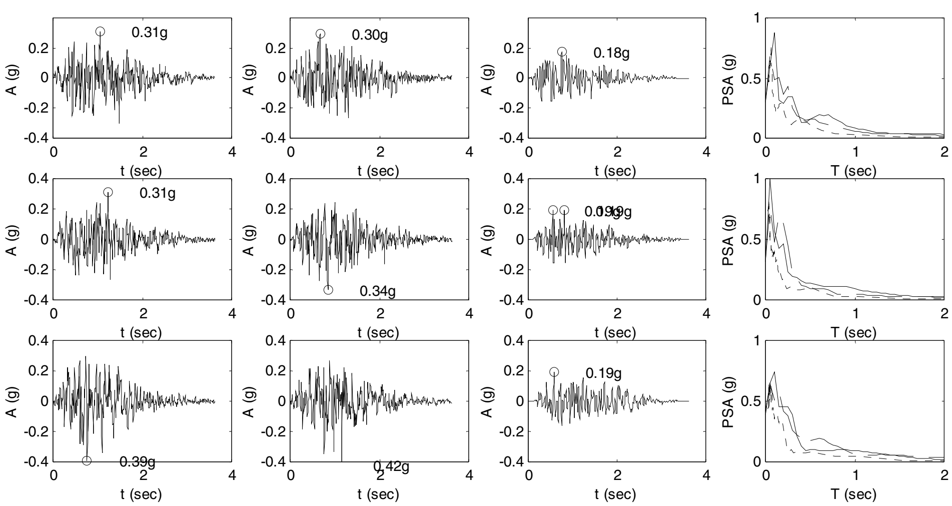


Figure C-1 New York : 2% Probability of Exceedance in 50 Years Long Ensemble (Cont'd)

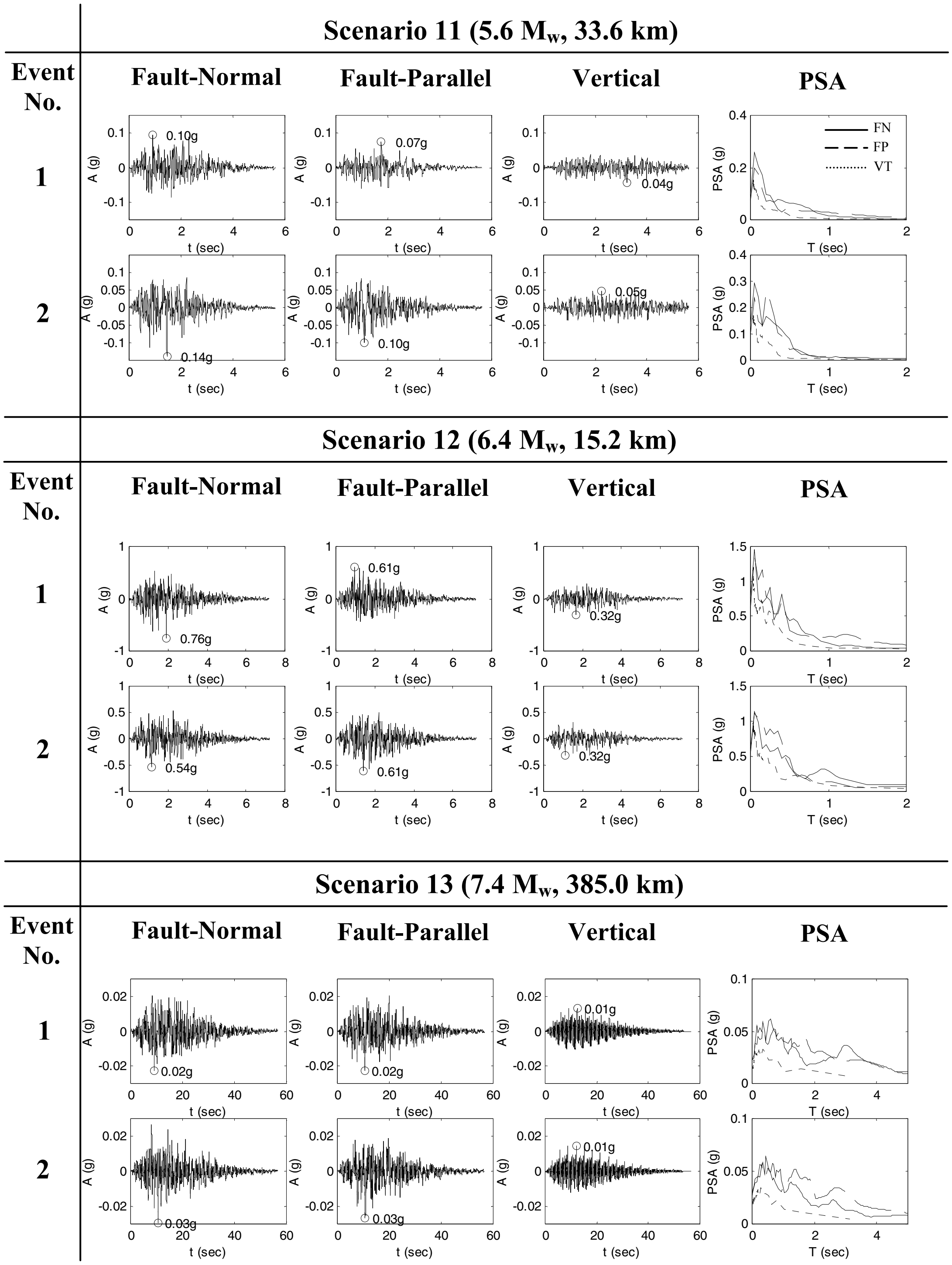


Figure C-1 New York : 2% Probability of Exceedance in 50 Years Long Ensemble (Cont'd)

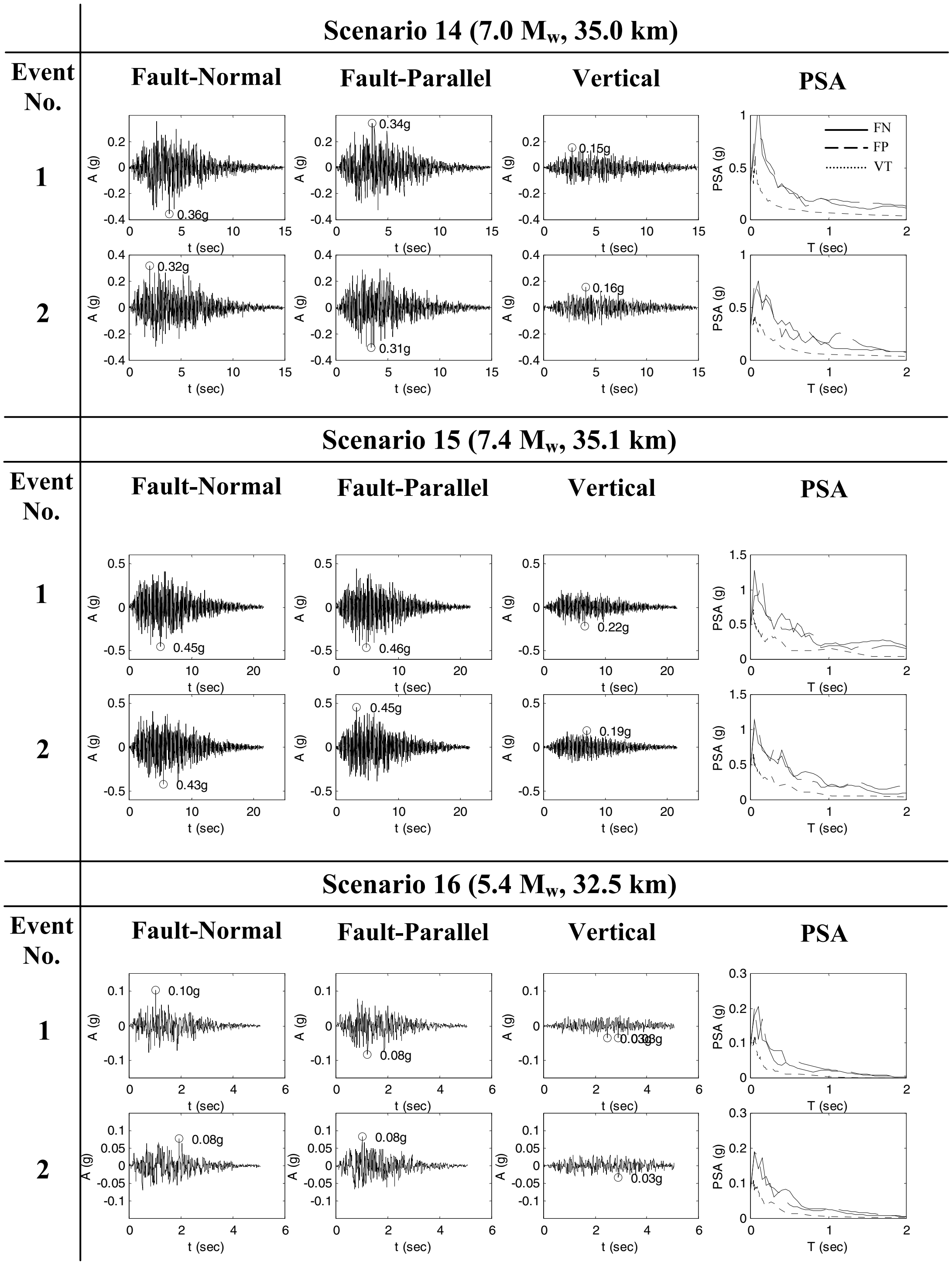


Figure C-1 New York : 2% Probability of Exceedance in 50 Years Long Ensemble (Cont'd)

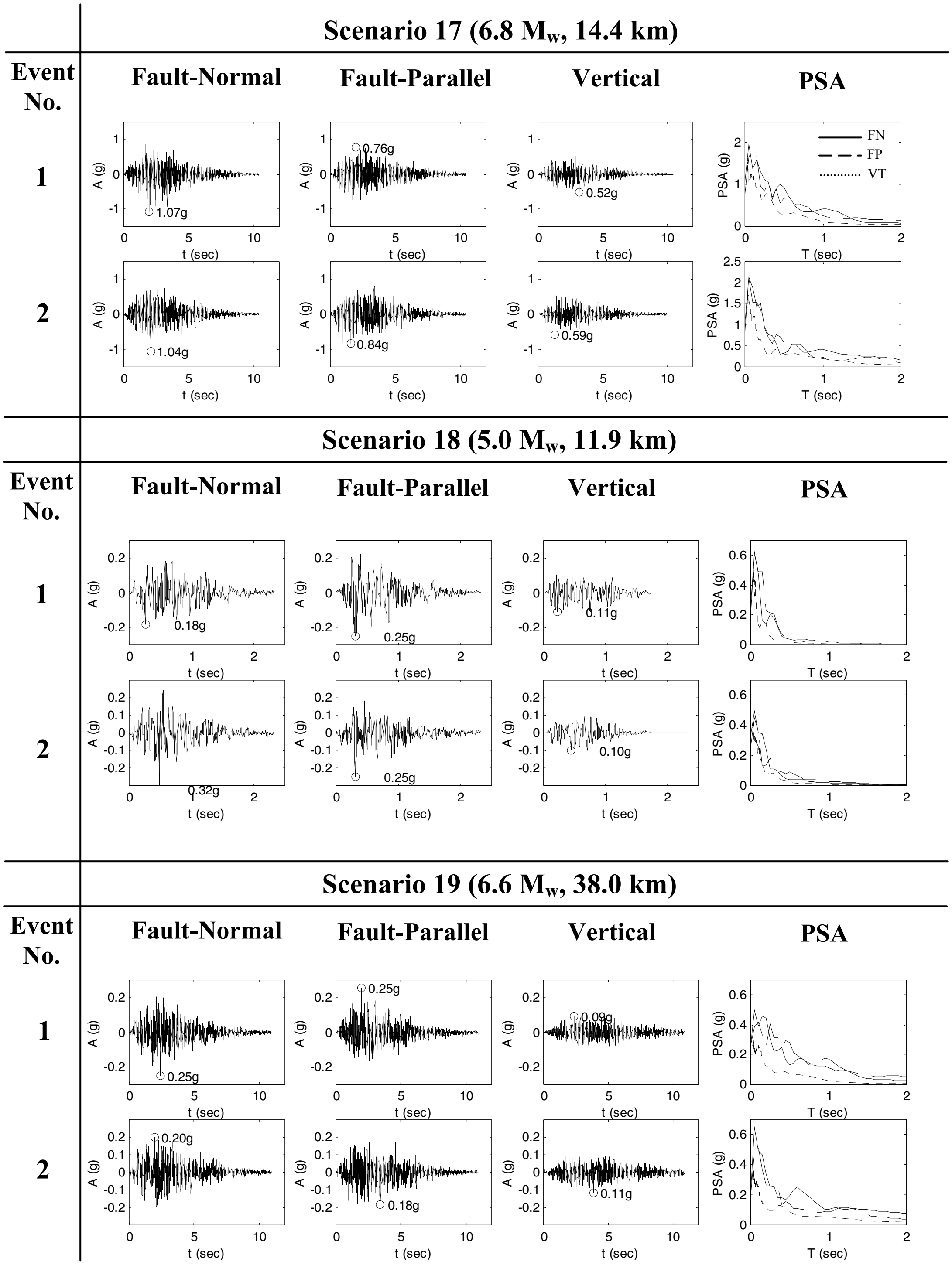
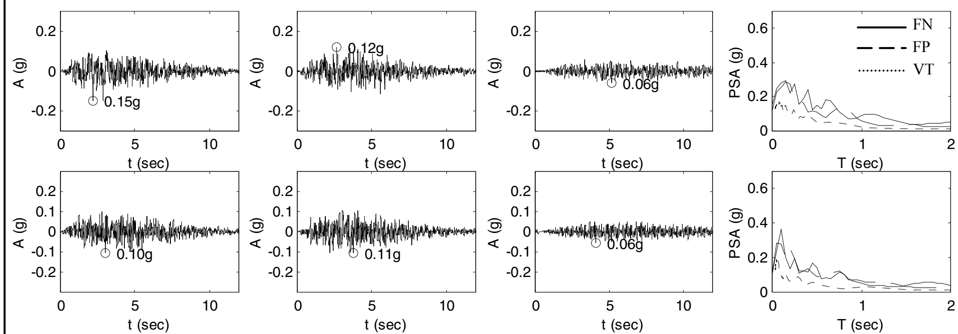


Figure C-1 New York : 2% Probability of Exceedance in 50 Years Long Ensemble (Cont'd)

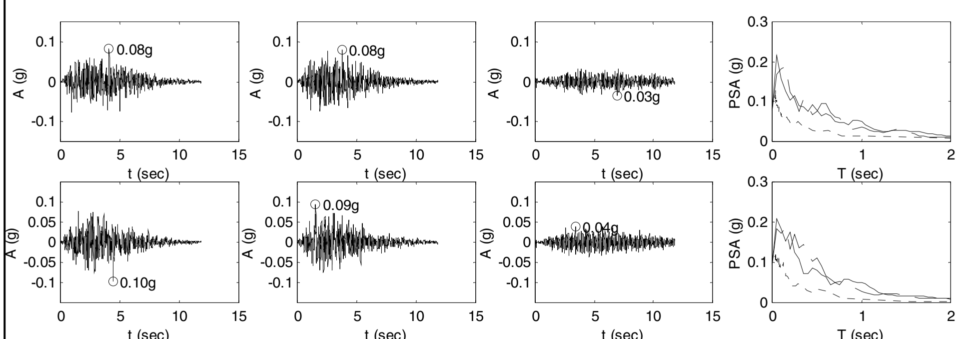
Scenario 20 (6.8 M_w, 61.9 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				
2				



Scenario 21 (6.4 M_w, 61.3 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				
2				



Scenario 22 (6.6 M_w, 16.0 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				
2				

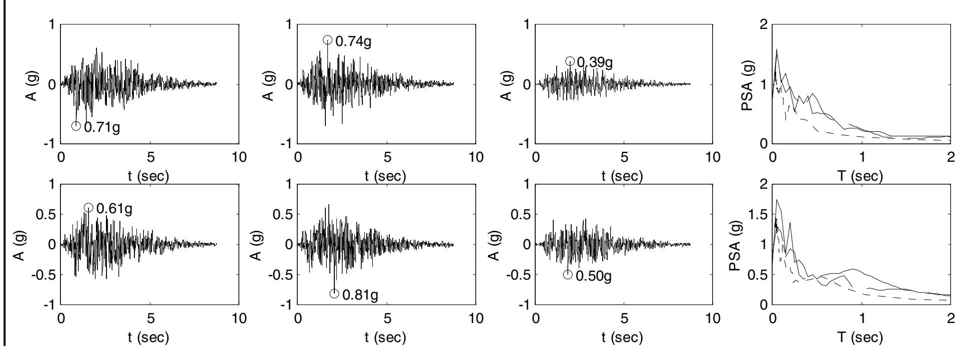


Figure C-1 New York : 2% Probability of Exceedance in 50 Years Long Ensemble (Cont'd)

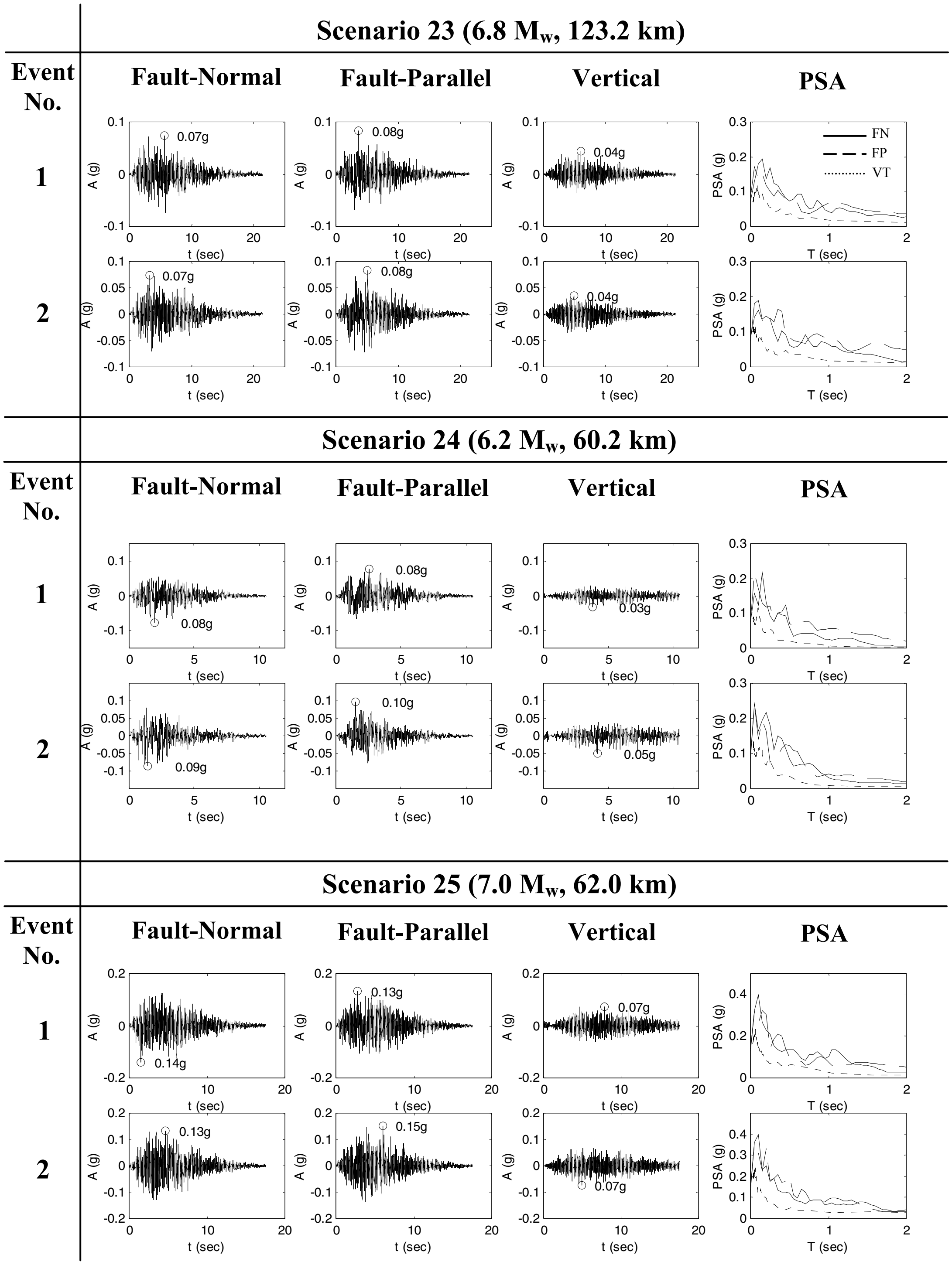
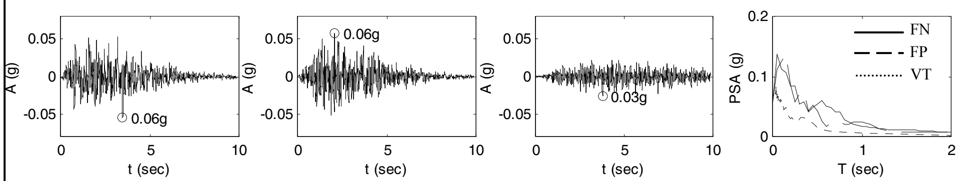


Figure C-1 New York : 2% Probability of Exceedance in 50 Years Long Ensemble (Cont'd)

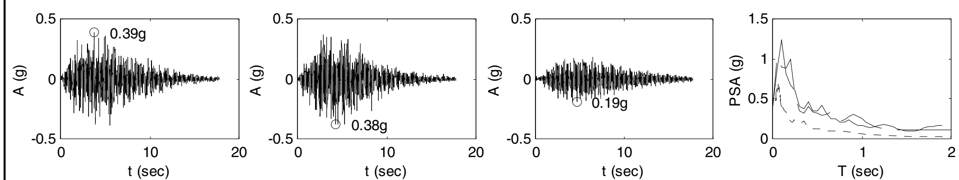
Scenario 26 (6.0 M_w, 62.9 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				



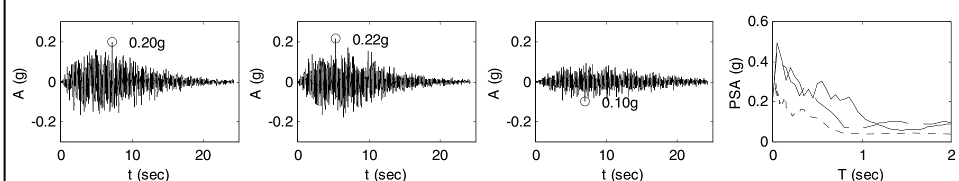
Scenario 27 (7.2 M_w, 34.8 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				



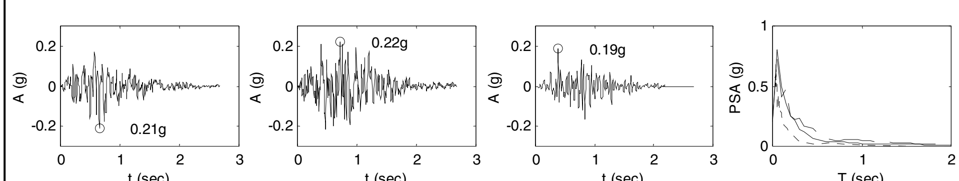
Scenario 28 (7.4 M_w, 62.3 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				



Scenario 29 (5.2 M_w, 12.5 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				



Scenario 30 (7.0 M_w, 13.3 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				

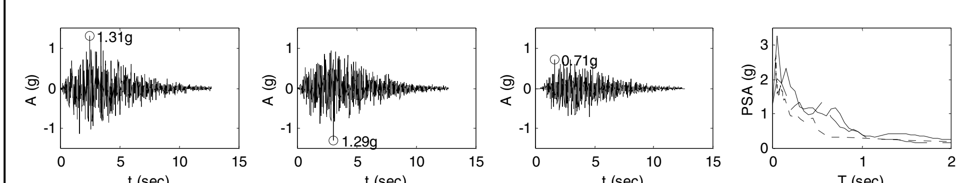


Figure C-1 New York : 2% Probability of Exceedance in 50 Years Long Ensemble (Cont'd)

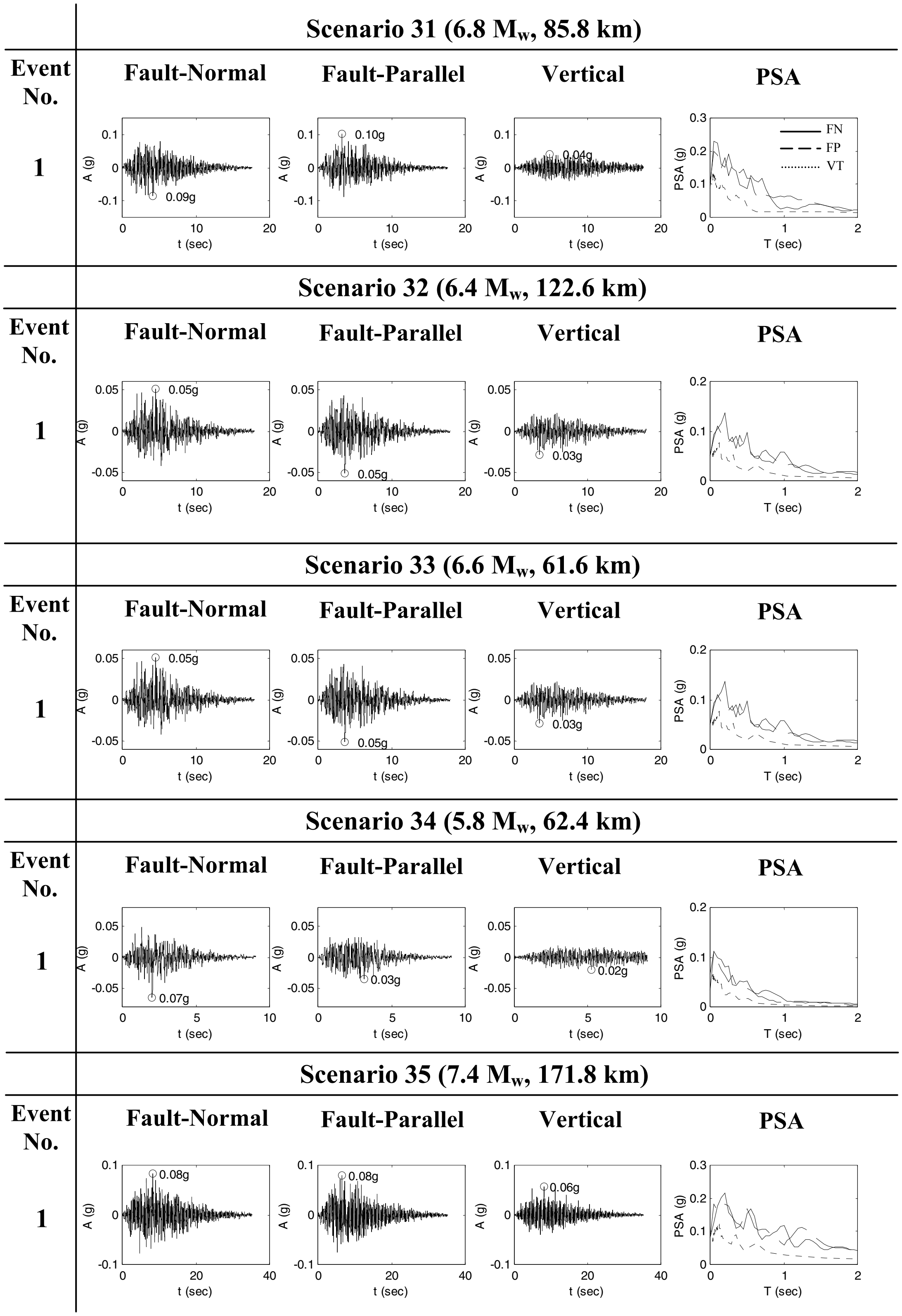


Figure C-1 New York : 2% Probability of Exceedance in 50 Years Long Ensemble (Cont'd)

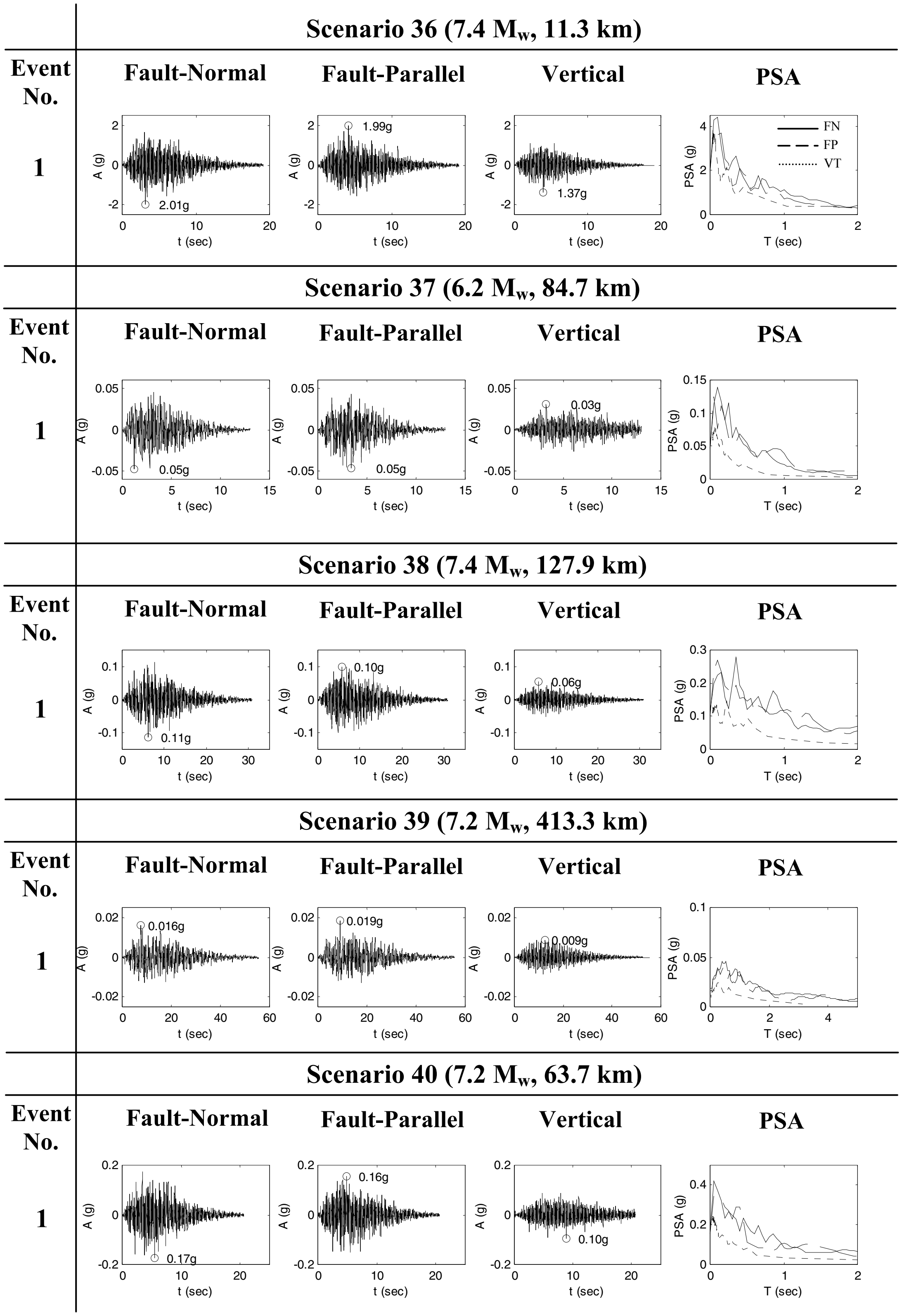
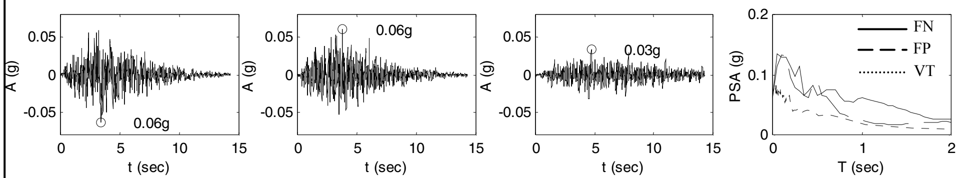


Figure C-1 New York : 2% Probability of Exceedance in 50 Years Long Ensemble (Cont'd)

Scenario 41 (6.4 M_w, 86.1 km)

Event No. | **Fault-Normal** | **Fault-Parallel** | **Vertical** | **PSA**

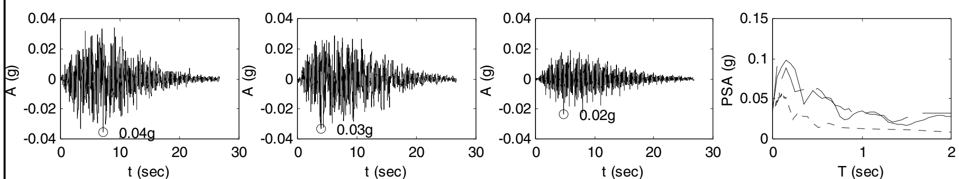
1



Scenario 42 (6.8 M_w, 177.0 km)

Event No. | **Fault-Normal** | **Fault-Parallel** | **Vertical** | **PSA**

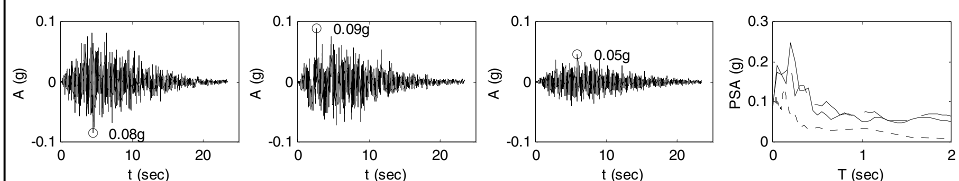
1



Scenario 43 (7.0 M_w, 120.4 km)

Event No. | **Fault-Normal** | **Fault-Parallel** | **Vertical** | **PSA**

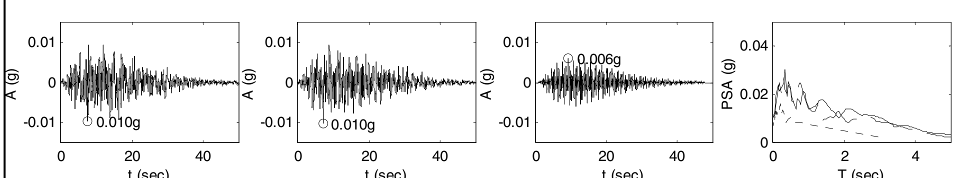
1



Scenario 44 (6.8 M_w, 410.4 km)

Event No. | **Fault-Normal** | **Fault-Parallel** | **Vertical** | **PSA**

1



Scenario 45 (7.0 M_w, 87.2 km)

Event No. | **Fault-Normal** | **Fault-Parallel** | **Vertical** | **PSA**

1

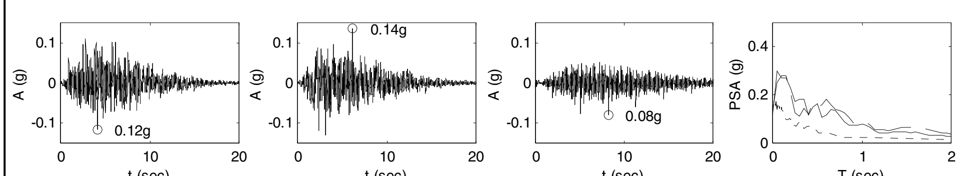
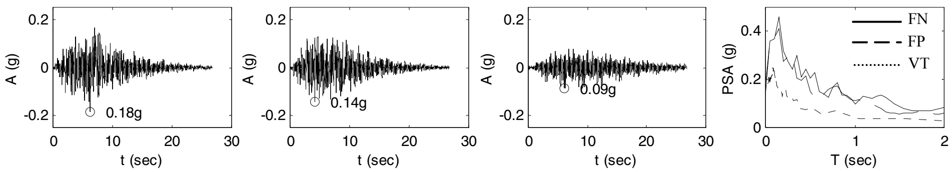


Figure C-1 New York : 2% Probability of Exceedance in 50 Years Long Ensemble (Cont'd)

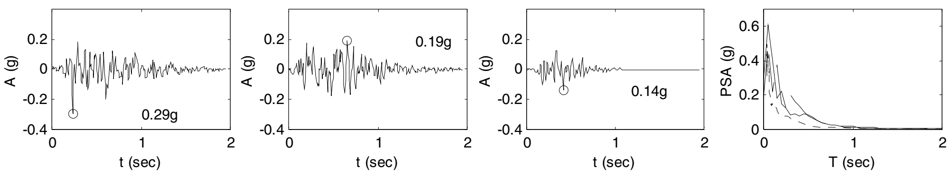
Scenario 46 (7.4 M_w, 87.2 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				



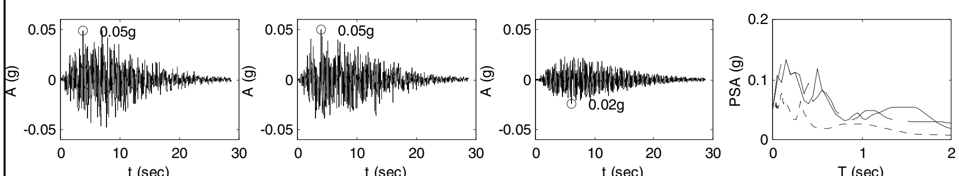
Scenario 47 (4.8 M_w, 10.6 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				



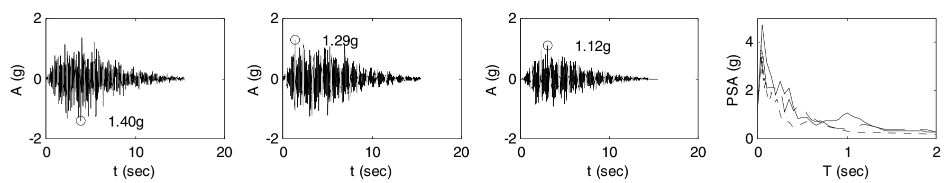
Scenario 48 (7.0 M_w, 173.0 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				



Scenario 49 (7.2 M_w, 11.8 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				



Scenario 50 (7.4 M_w, 222.5 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				

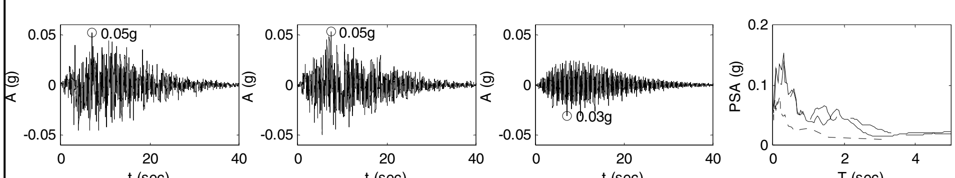
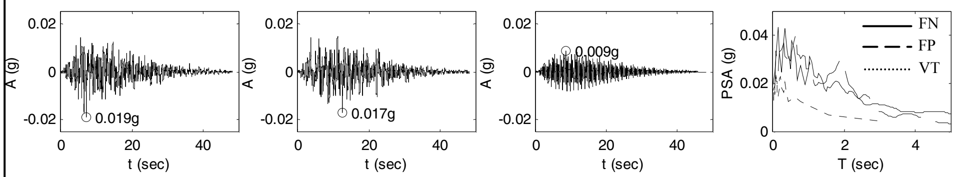


Figure C-1 New York : 2% Probability of Exceedance in 50 Years Long Ensemble (Cont'd)

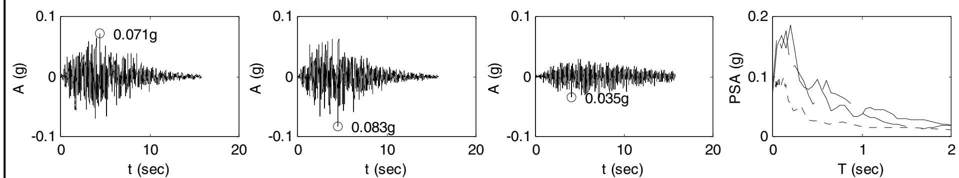
Scenario 51 (7.0 M_w, 367.7 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				



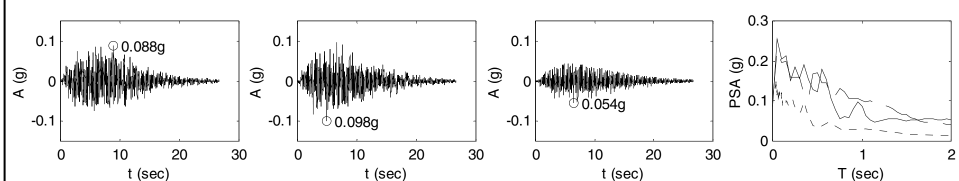
Scenario 52 (6.6 M_w, 85.8 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				



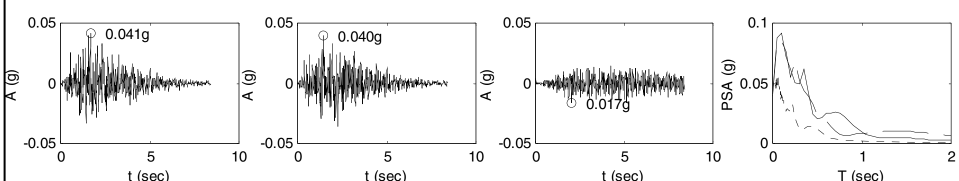
Scenario 53 (7.2 M_w, 124.0 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				



Scenario 54 (5.6 M_w, 61.4 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				



Scenario 55 (7.4 M_w, 278.6 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				

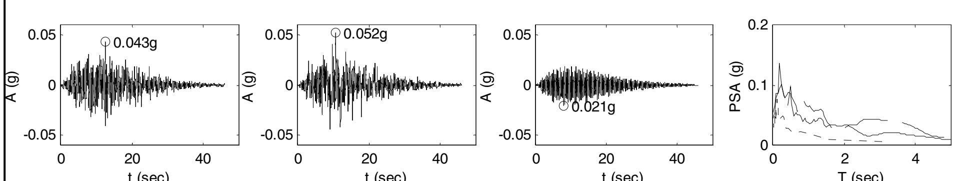
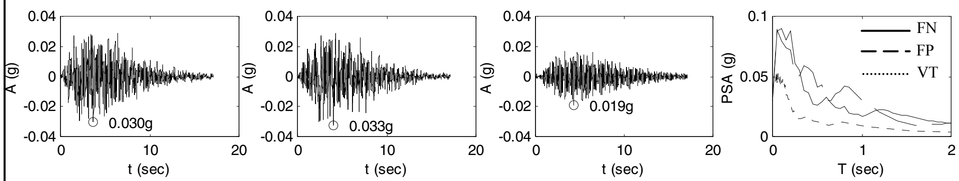
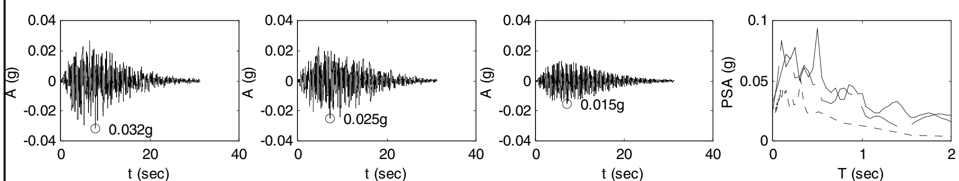


Figure C-1 New York : 2% Probability of Exceedance in 50 Years Long Ensemble (Cont'd)

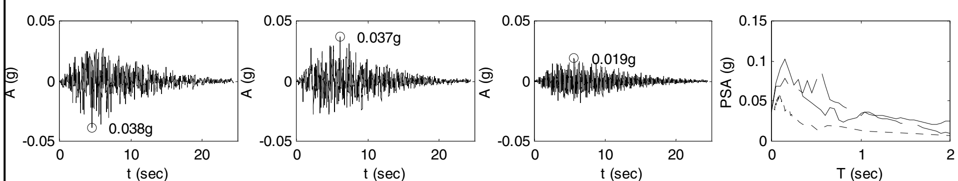
Event No.	Scenario 56 (6.2 M_w, 126.3 km)			
	Fault-Normal	**Fault-Parallel**	**Vertical**	**PSA**
1				



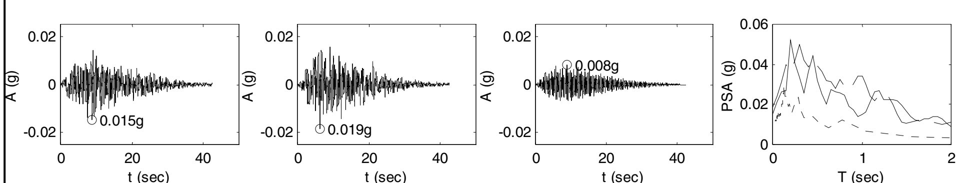
Event No.	Scenario 57 (6.8 M_w, 222.1 km)			
	Fault-Normal	**Fault-Parallel**	**Vertical**	**PSA**
1				



Event No.	Scenario 58 (6.6 M_w, 172.2 km)			
	Fault-Normal	**Fault-Parallel**	**Vertical**	**PSA**
1				



Event No.	Scenario 59 (6.8 M_w, 335.4 km)			
	Fault-Normal	**Fault-Parallel**	**Vertical**	**PSA**
1				



Event No.	Scenario 60 (7.2 M_w, 337.0 km)			
	Fault-Normal	**Fault-Parallel**	**Vertical**	**PSA**
1				

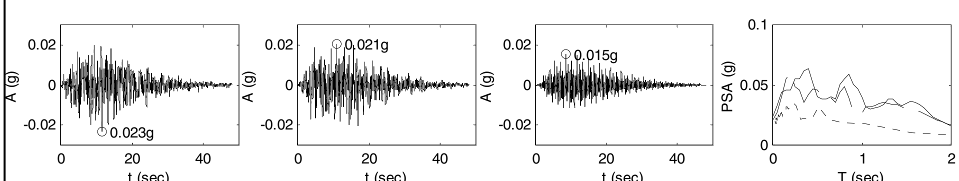
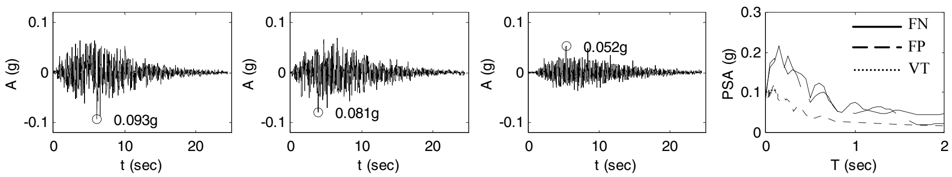


Figure C-1 New York : 2% Probability of Exceedance in 50 Years Long Ensemble (Cont'd)

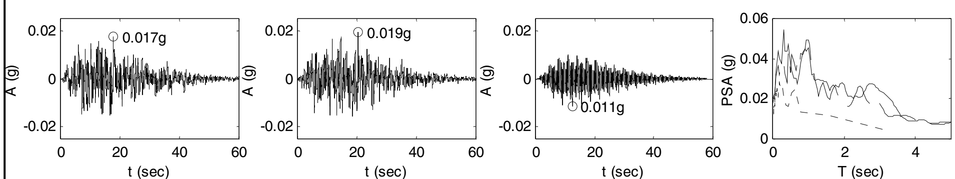
Scenario 61 (7.0 M_w, 130.9 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				



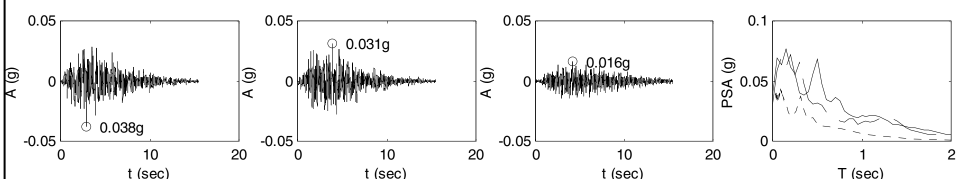
Scenario 62 (7.4 M_w, 431.7 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				



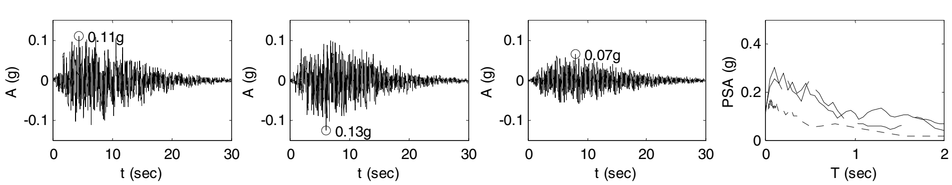
Scenario 63 (6.0 M_w, 119.0 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				



Scenario 64 (7.4 M_w, 118.4 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				



Scenario 65 (6.6 M_w, 129.9 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				

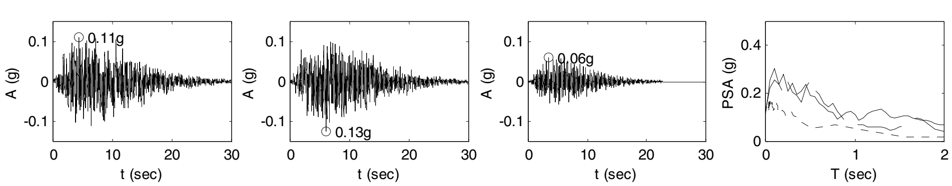


Figure C-1 New York : 2% Probability of Exceedance in 50 Years Long Ensemble (Cont'd)

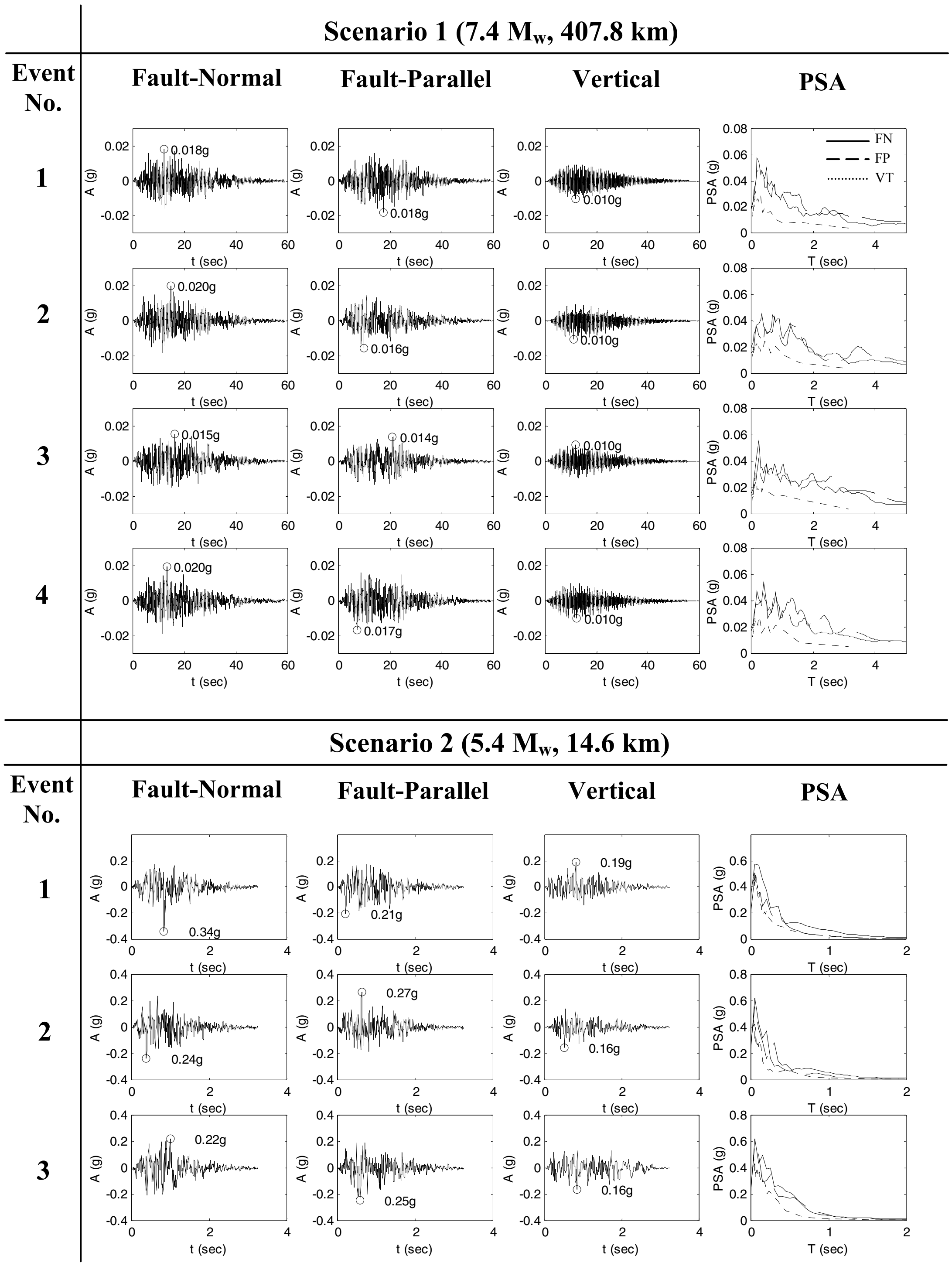
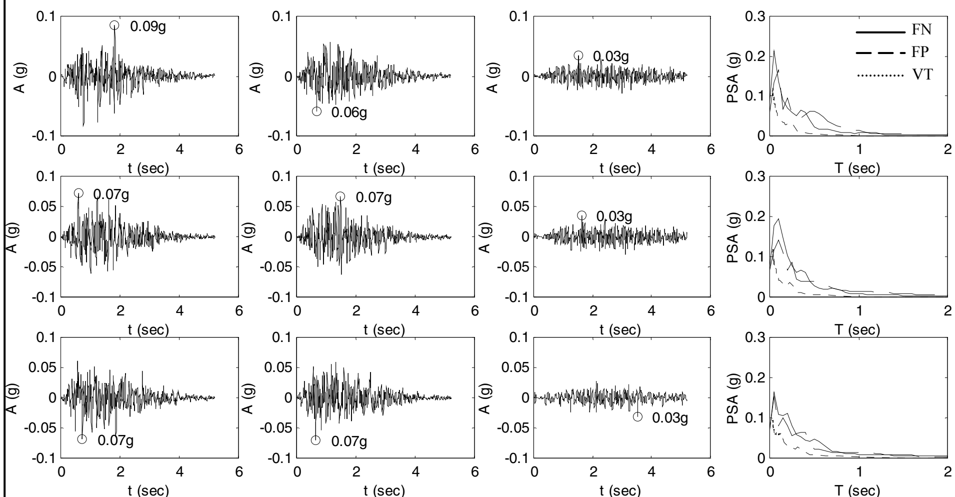


Figure C-2 New York : 5% Probability of Exceedance in 50 Years Long Ensemble

Scenario 3 (5.4 M_w, 34.1 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				
2				
3				



Scenario 4 (6.2 M_w, 35.6 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				
2				
3				

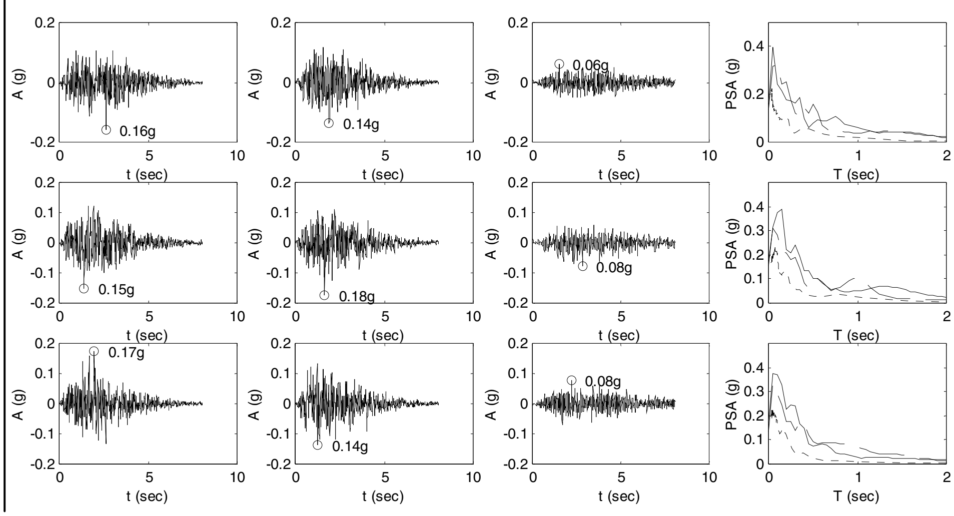
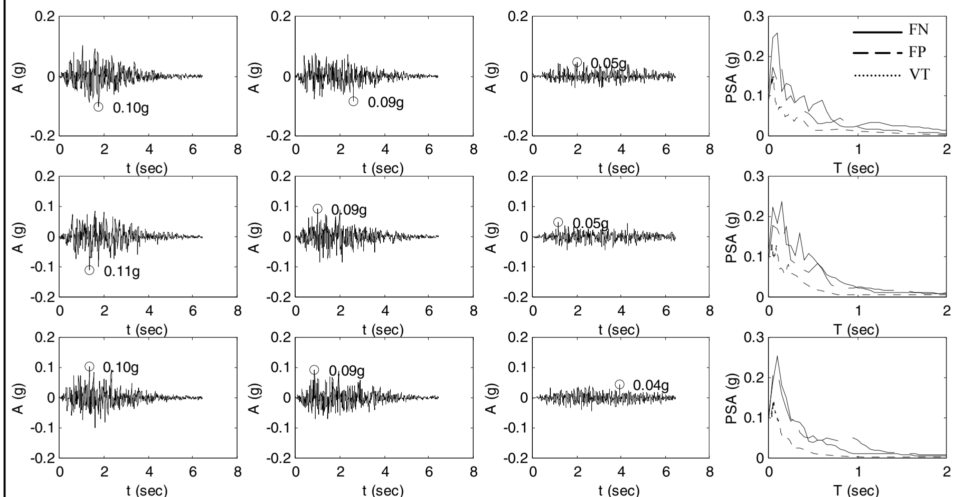


Figure C-2 New York : 5% Probability of Exceedance in 50 Years Long Ensemble (Cont'd)

Scenario 5 (5.8 M_w, 36.2 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				
2				
3				



Scenario 6 (5.0 M_w, 14.5 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				
2				
3				

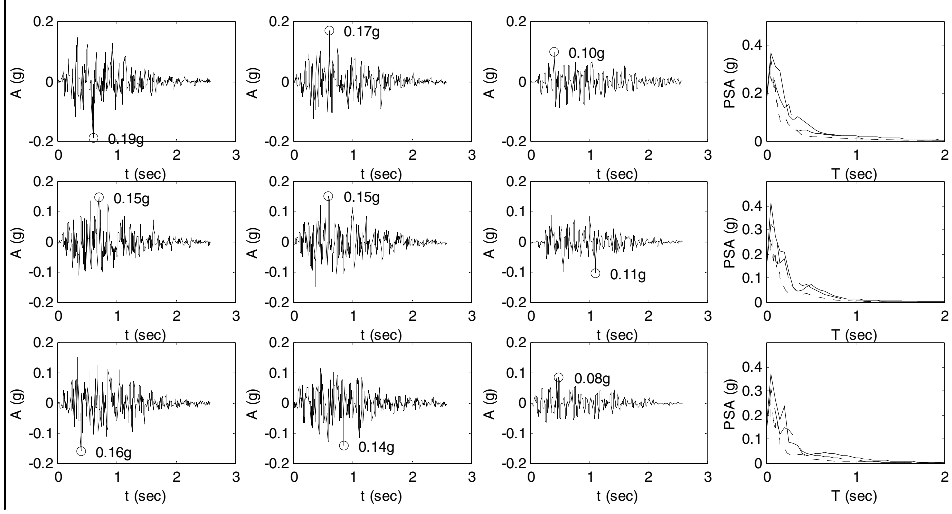


Figure C-2 New York : 5% Probability of Exceedance in 50 Years Long Ensemble (Cont'd)

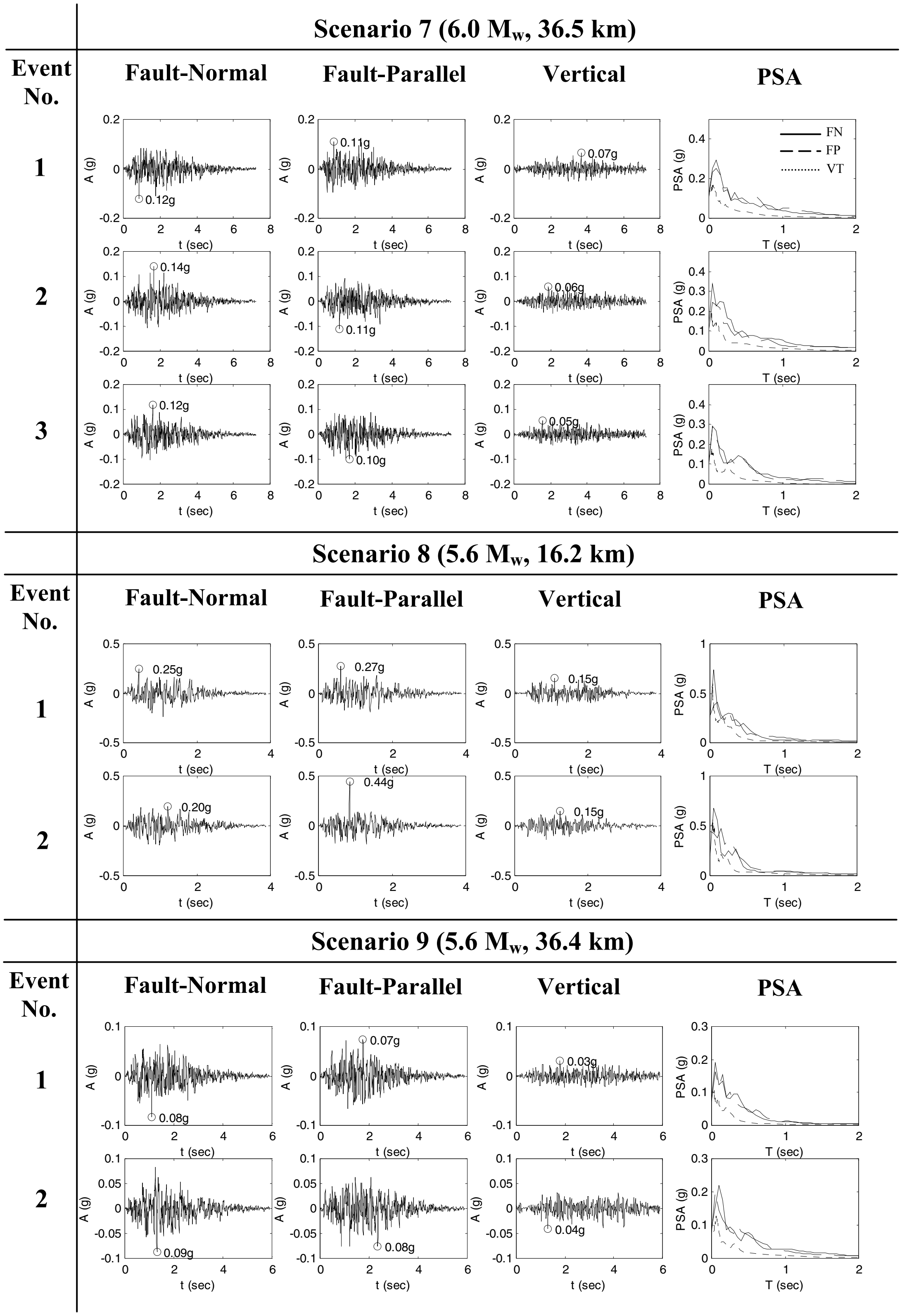


Figure C-2 New York : 5% Probability of Exceedance in 50 Years Long Ensemble (Cont'd)

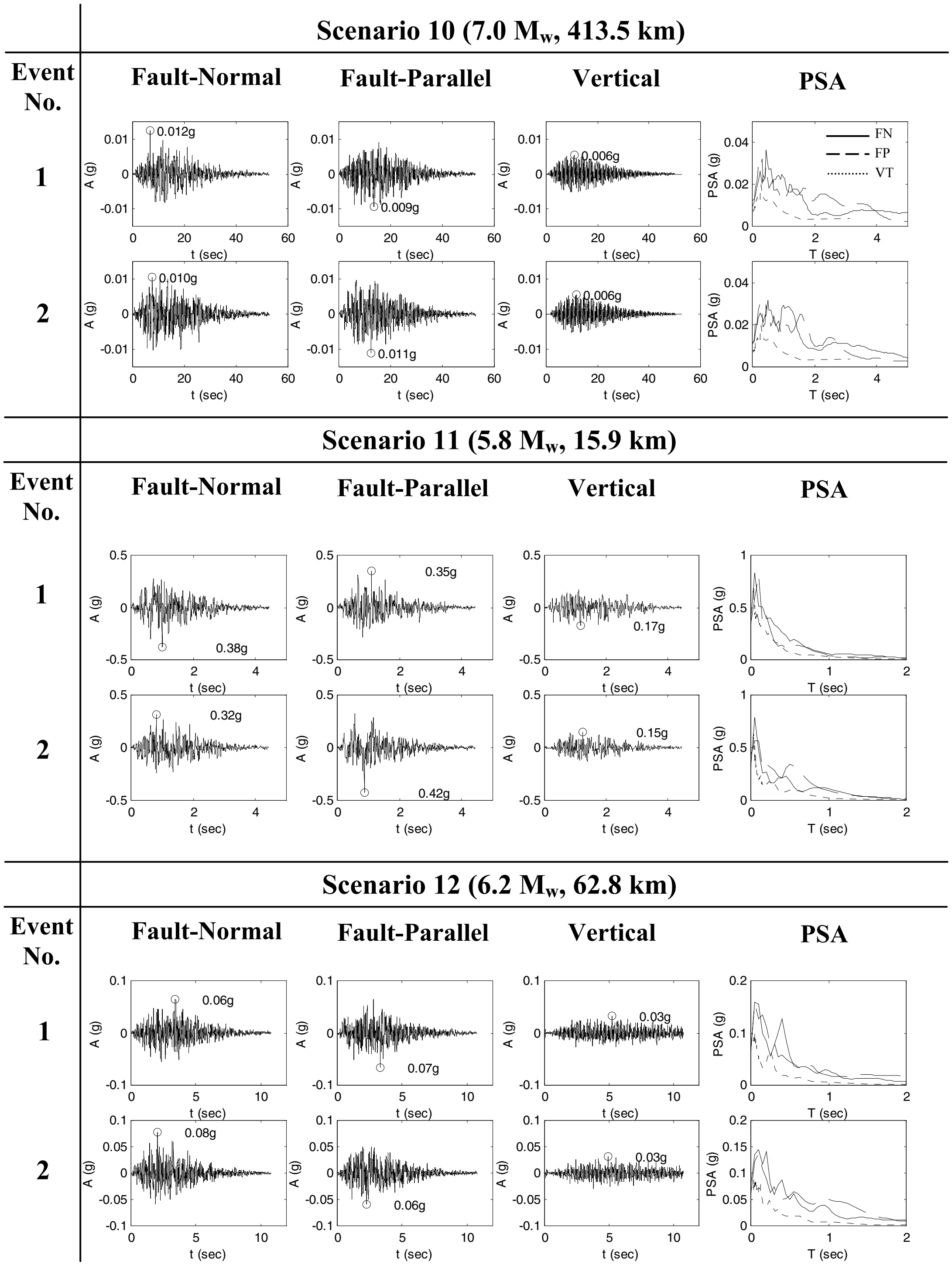


Figure C-2 New York : 5% Probability of Exceedance in 50 Years Long Ensemble (Cont'd)

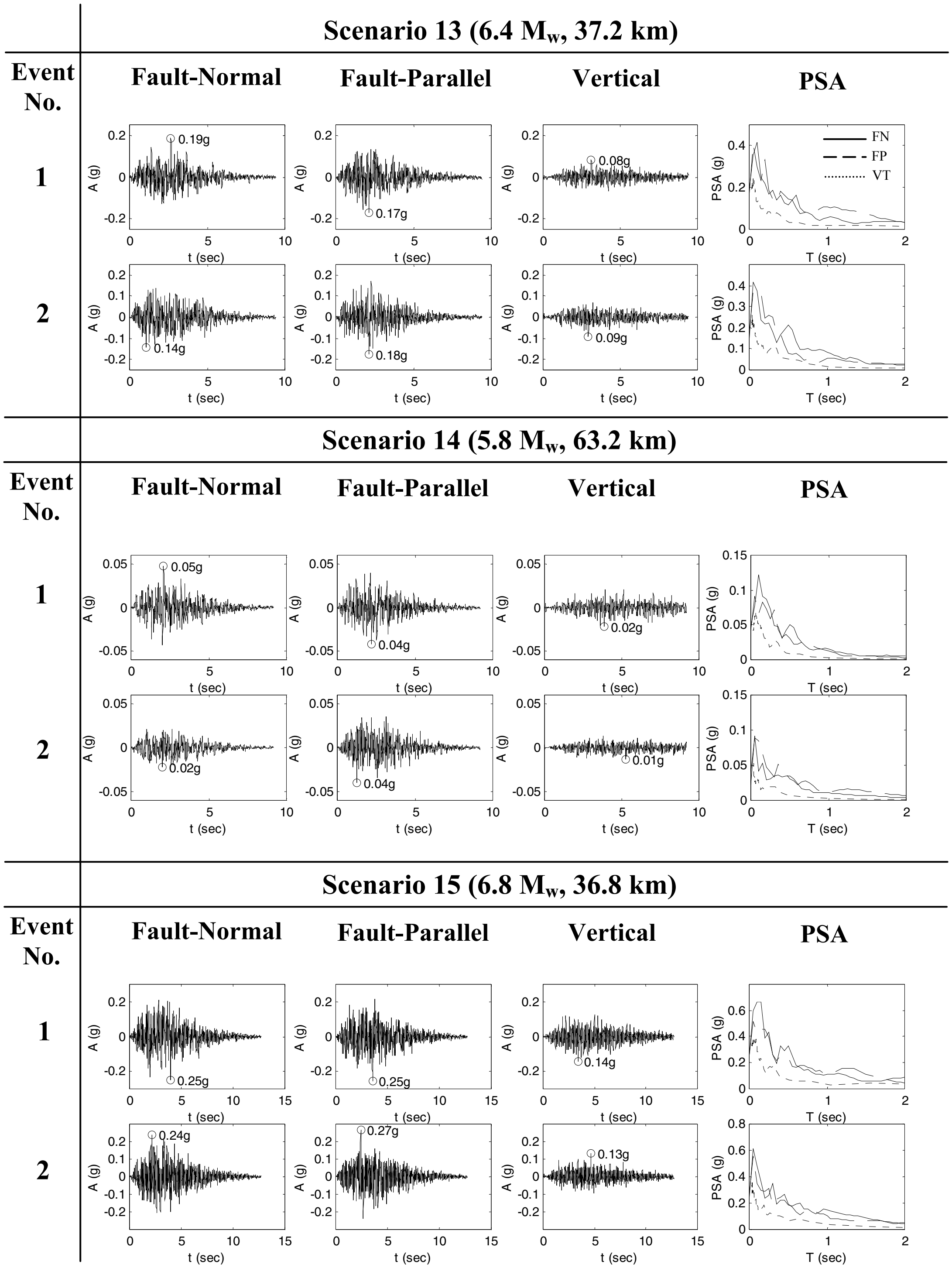


Figure C-2 New York : 5% Probability of Exceedance in 50 Years Long Ensemble (Cont'd)

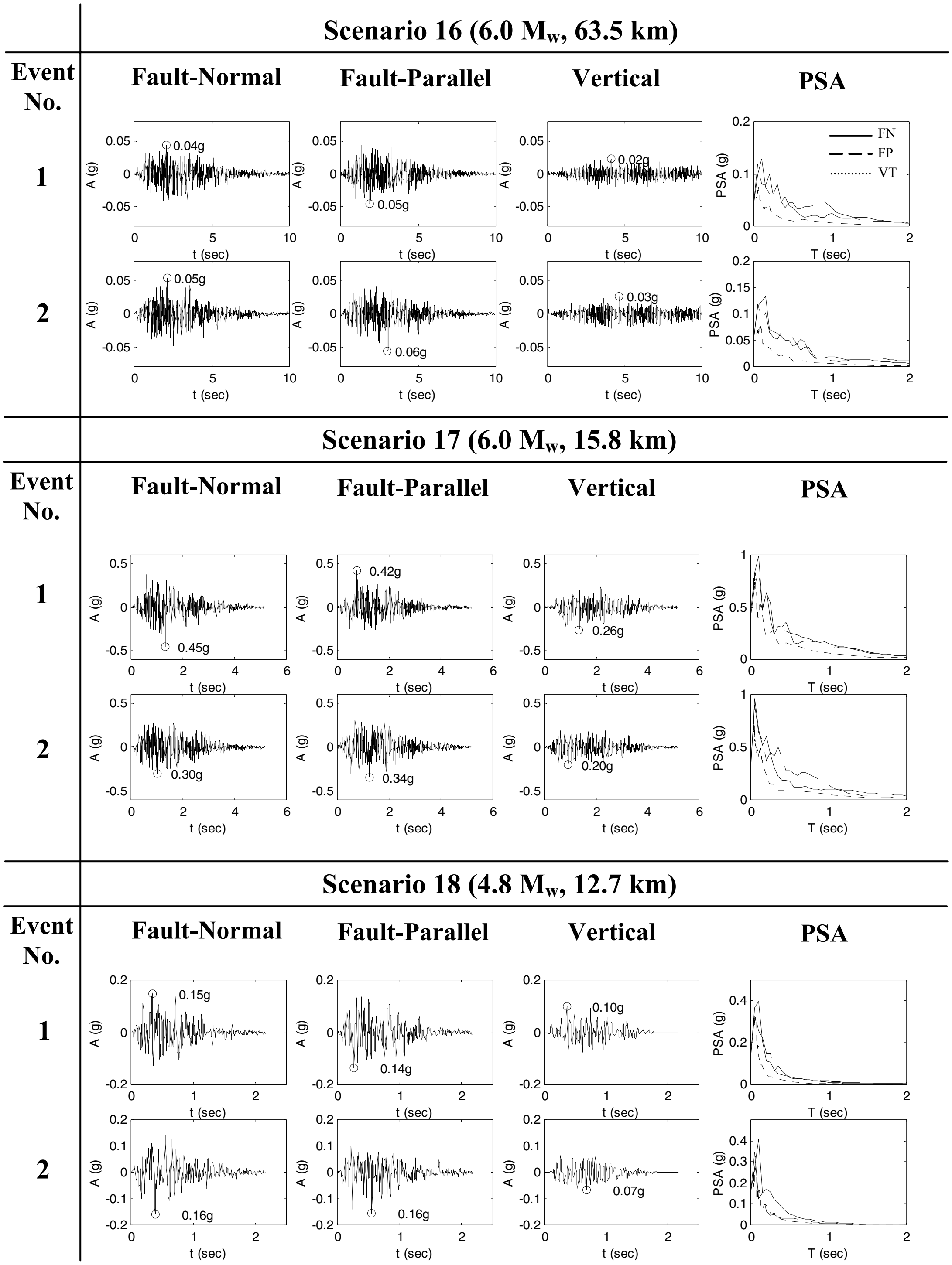


Figure C-2 New York : 5% Probability of Exceedance in 50 Years Long Ensemble (Cont'd)

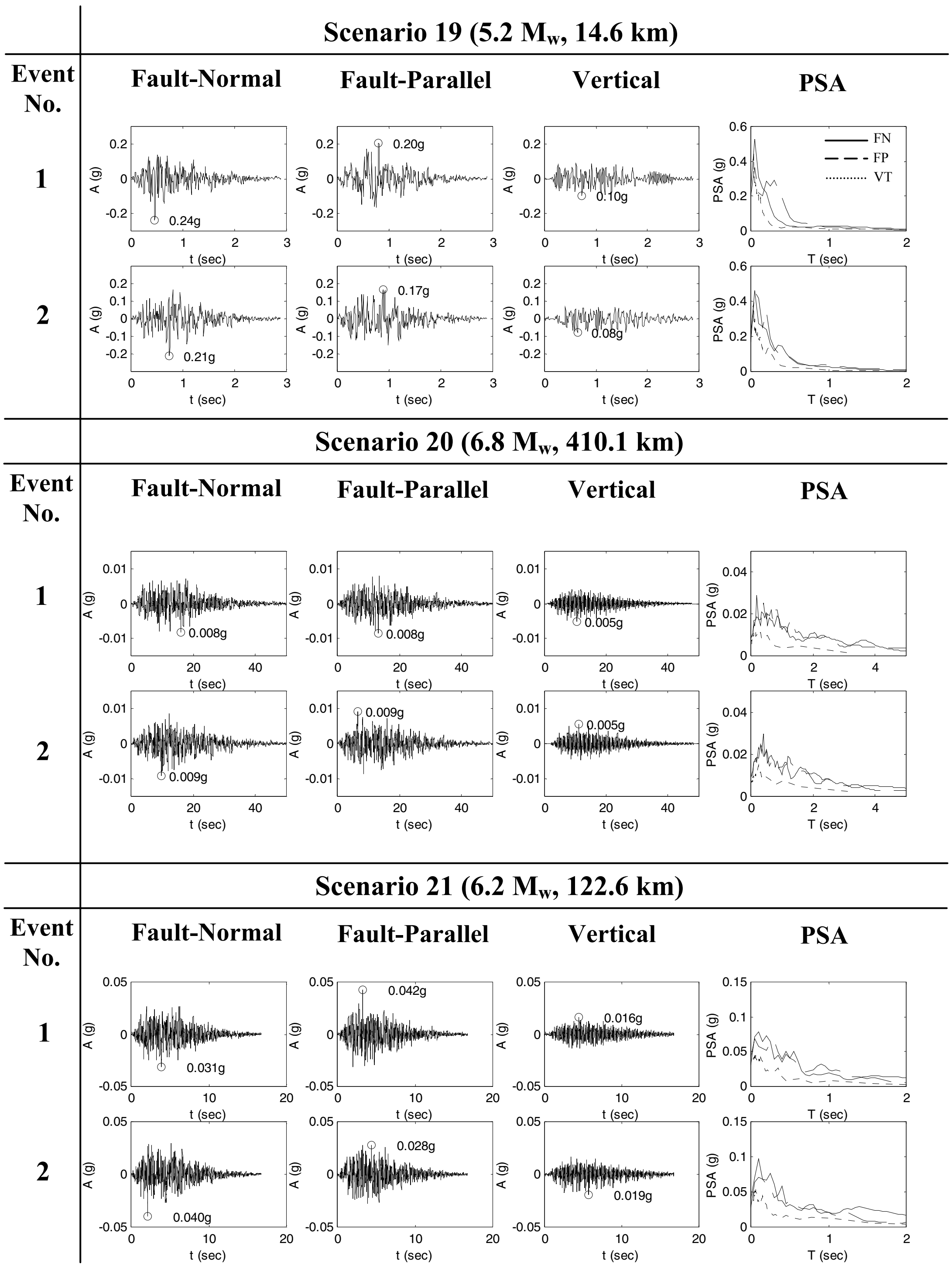
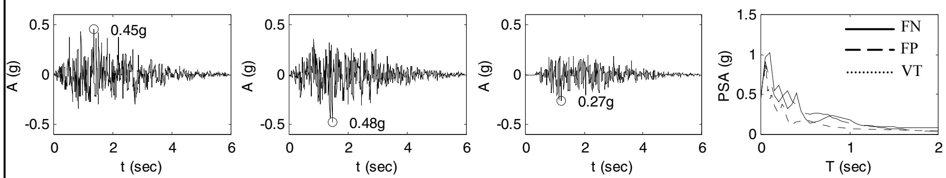


Figure C-2 New York : 5% Probability of Exceedance in 50 Years Long Ensemble (Cont'd)

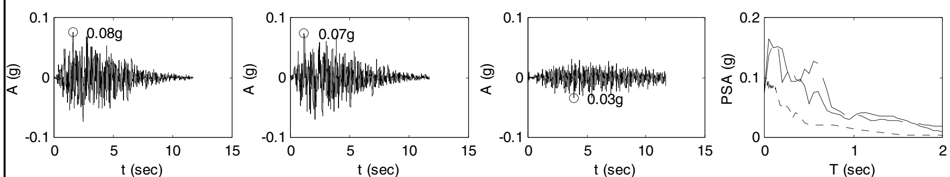
Scenario 22 (6.2 M_w, 14.3 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				



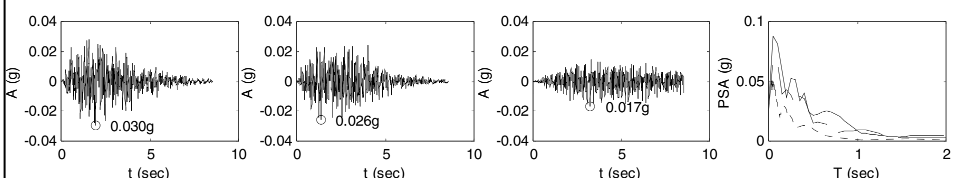
Scenario 23 (6.4 M_w, 60.3 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				



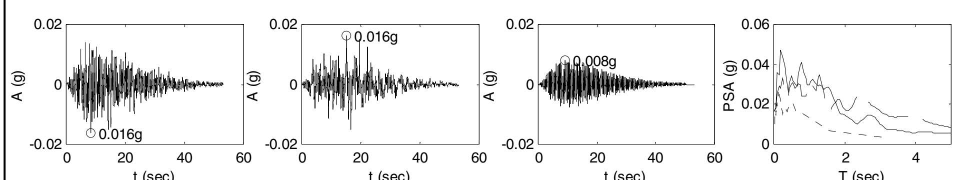
Scenario 24 (5.6 M_w, 62.7 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				



Scenario 25 (7.2 M_w, 387.6 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				



Scenario 26 (6.8 M_w, 173.8 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				

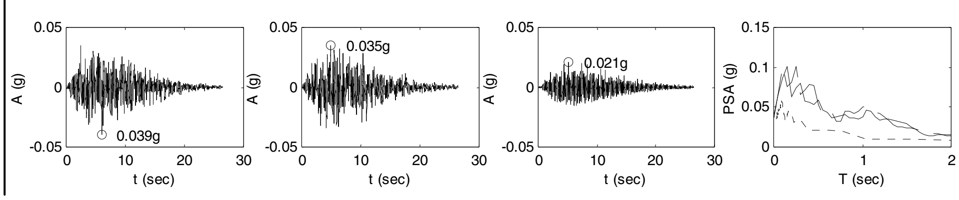
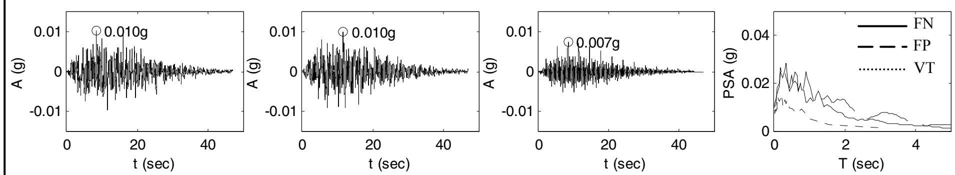


Figure C-2 New York : 5% Probability of Exceedance in 50 Years Long Ensemble (Cont'd)

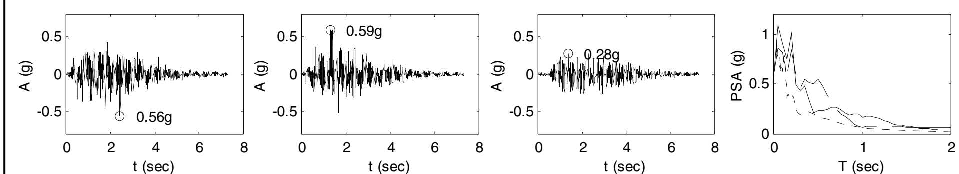
Scenario 27 (6.8 M_w, 378.9 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				



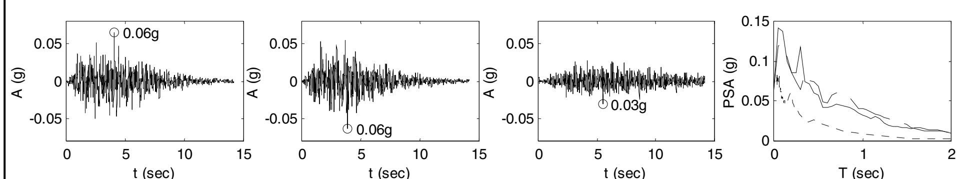
Scenario 28 (6.4 M_w, 16.3 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				



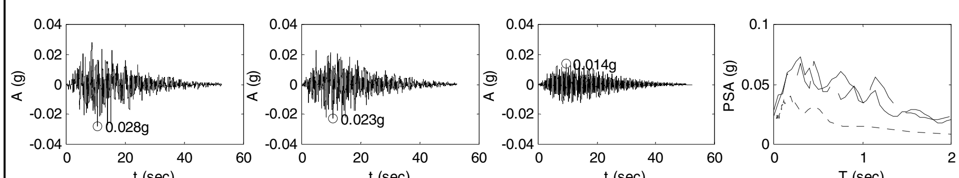
Scenario 29 (6.4 M_w, 84.9 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				



Scenario 30 (7.4 M_w, 343.9 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				



Scenario 31 (6.6 M_w, 37.2 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				

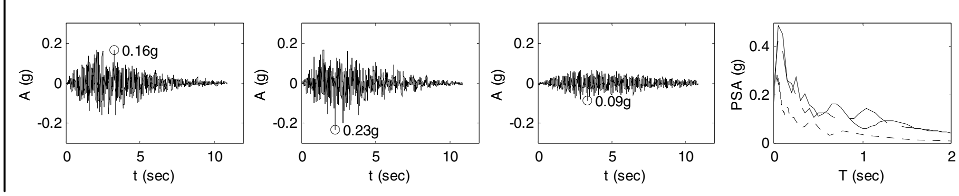
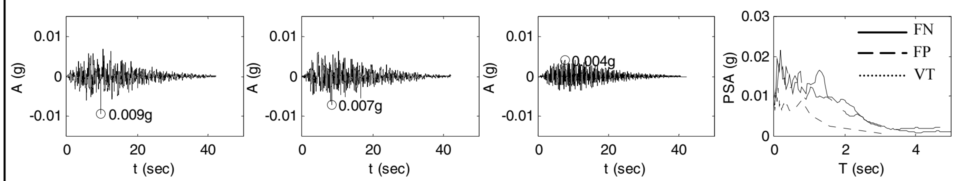


Figure C-2 New York : 5% Probability of Exceedance in 50 Years Long Ensemble (Cont'd)

Scenario 32 (6.4 M_w, 363.9 km)

Event No. | **Fault-Normal** | **Fault-Parallel** | **Vertical** | **PSA**

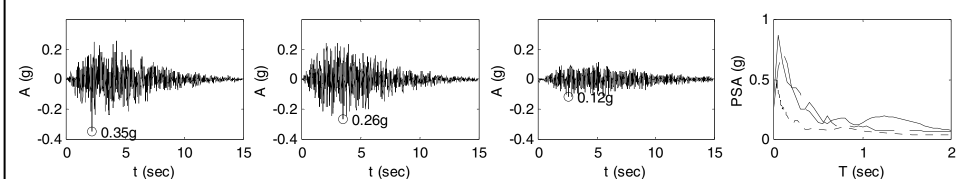
1



Scenario 33 (7.0 M_w, 35.2 km)

Event No. | **Fault-Normal** | **Fault-Parallel** | **Vertical** | **PSA**

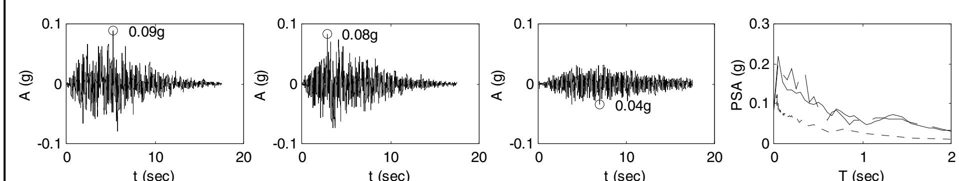
1



Scenario 34 (6.8 M_w, 84.9 km)

Event No. | **Fault-Normal** | **Fault-Parallel** | **Vertical** | **PSA**

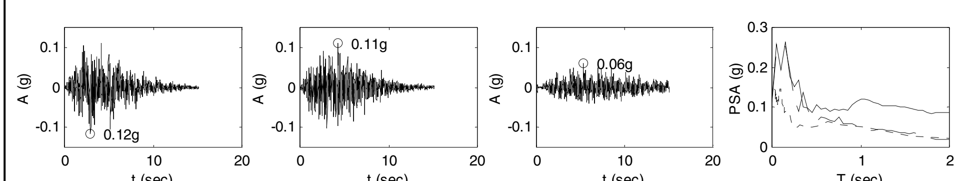
1



Scenario 35 (6.8 M_w, 61.1 km)

Event No. | **Fault-Normal** | **Fault-Parallel** | **Vertical** | **PSA**

1



Scenario 36 (5.4 M_w, 62.2 km)

Event No. | **Fault-Normal** | **Fault-Parallel** | **Vertical** | **PSA**

1

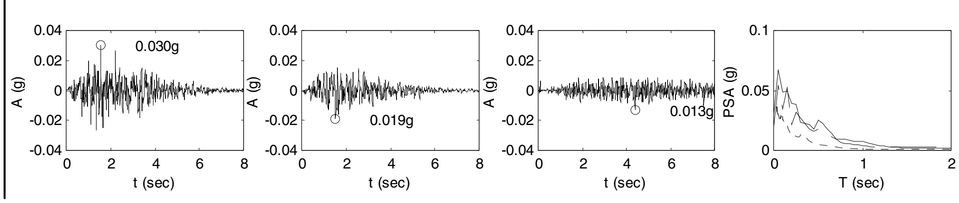


Figure C-2 New York : 5% Probability of Exceedance in 50 Years Long Ensemble (Cont'd)

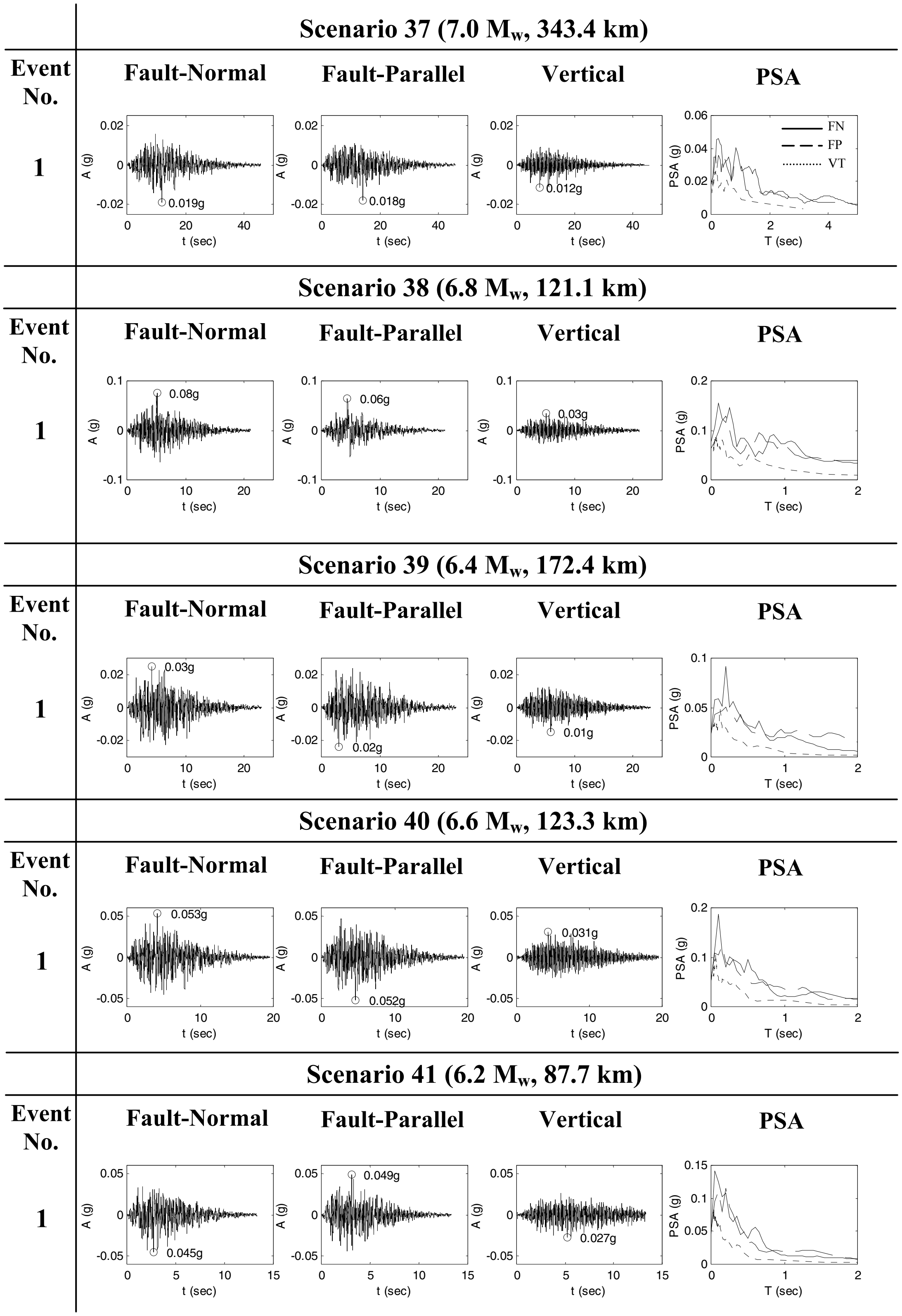


Figure C-2 New York : 5% Probability of Exceedance in 50 Years Long Ensemble (Cont'd)

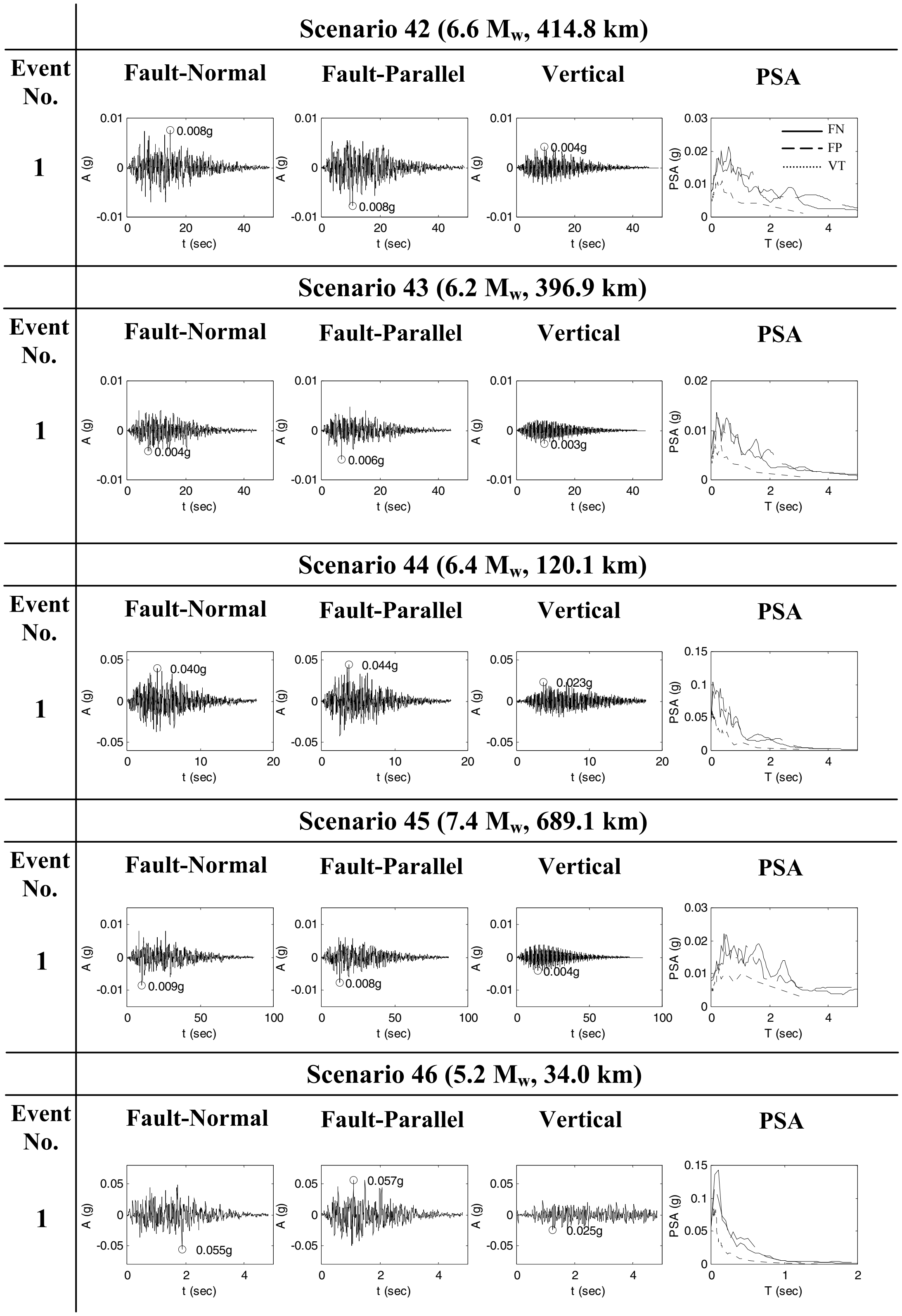
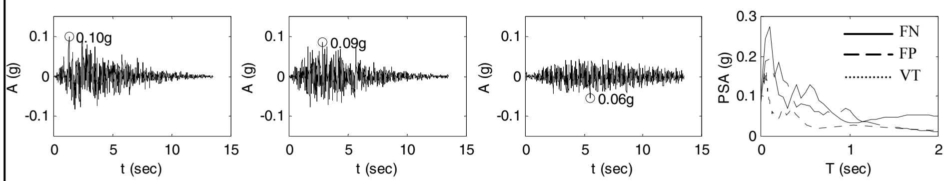


Figure C-2 New York : 5% Probability of Exceedance in 50 Years Long Ensemble (Cont'd)

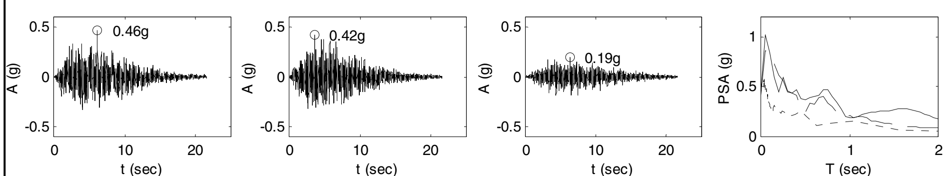
Scenario 47 (6.6 M_w, 63.1 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				



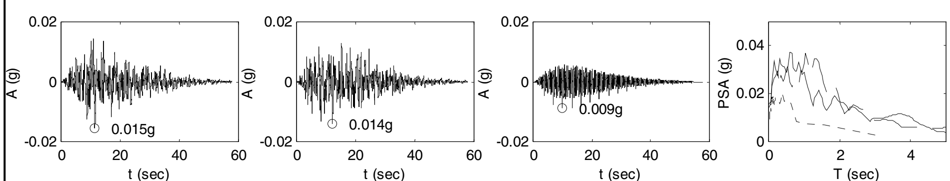
Scenario 48 (7.4 M_w, 35.5 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				



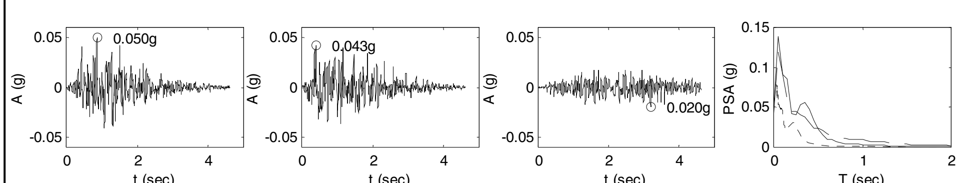
Scenario 49 (7.2 M_w, 433.9 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				



Scenario 50 (5.0 M_w, 34.8 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				



Scenario 51 (7.4 M_w, 124.6 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				

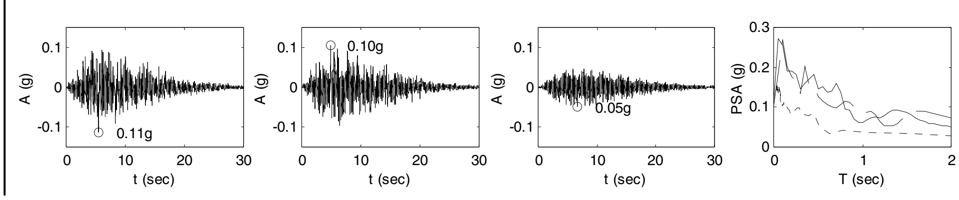
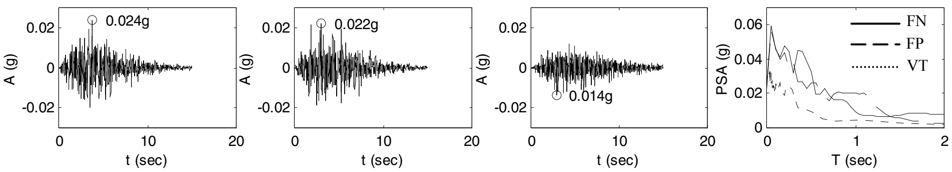


Figure C-2 New York : 5% Probability of Exceedance in 50 Years Long Ensemble (Cont'd)

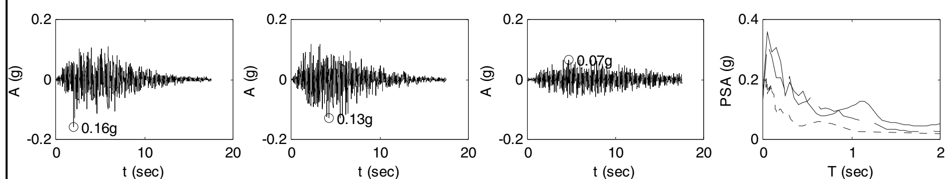
Scenario 52 (5.8 M_w, 121.0 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				



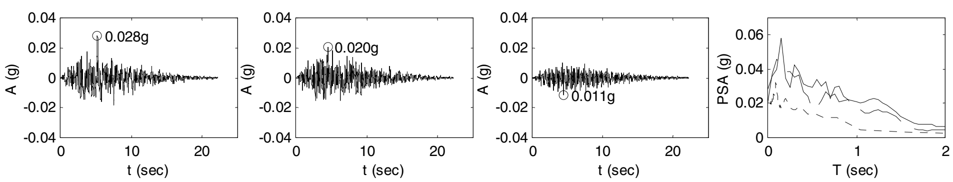
Scenario 53 (7.0 M_w, 61.9 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				



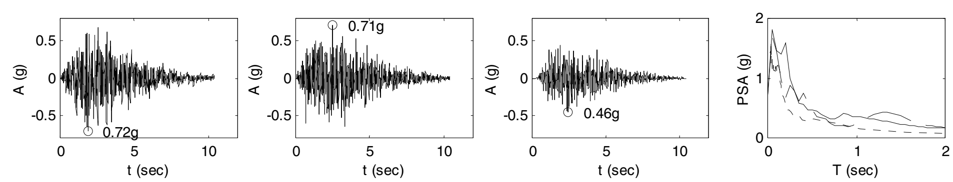
Scenario 54 (6.2 M_w, 176.2 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				



Scenario 55 (6.8 M_w, 14.4 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				



Scenario 56 (7.4 M_w, 278.8 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				

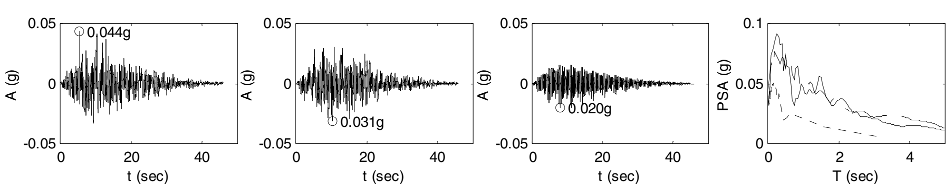


Figure C-2 New York : 5% Probability of Exceedance in 50 Years Long Ensemble (Cont'd)

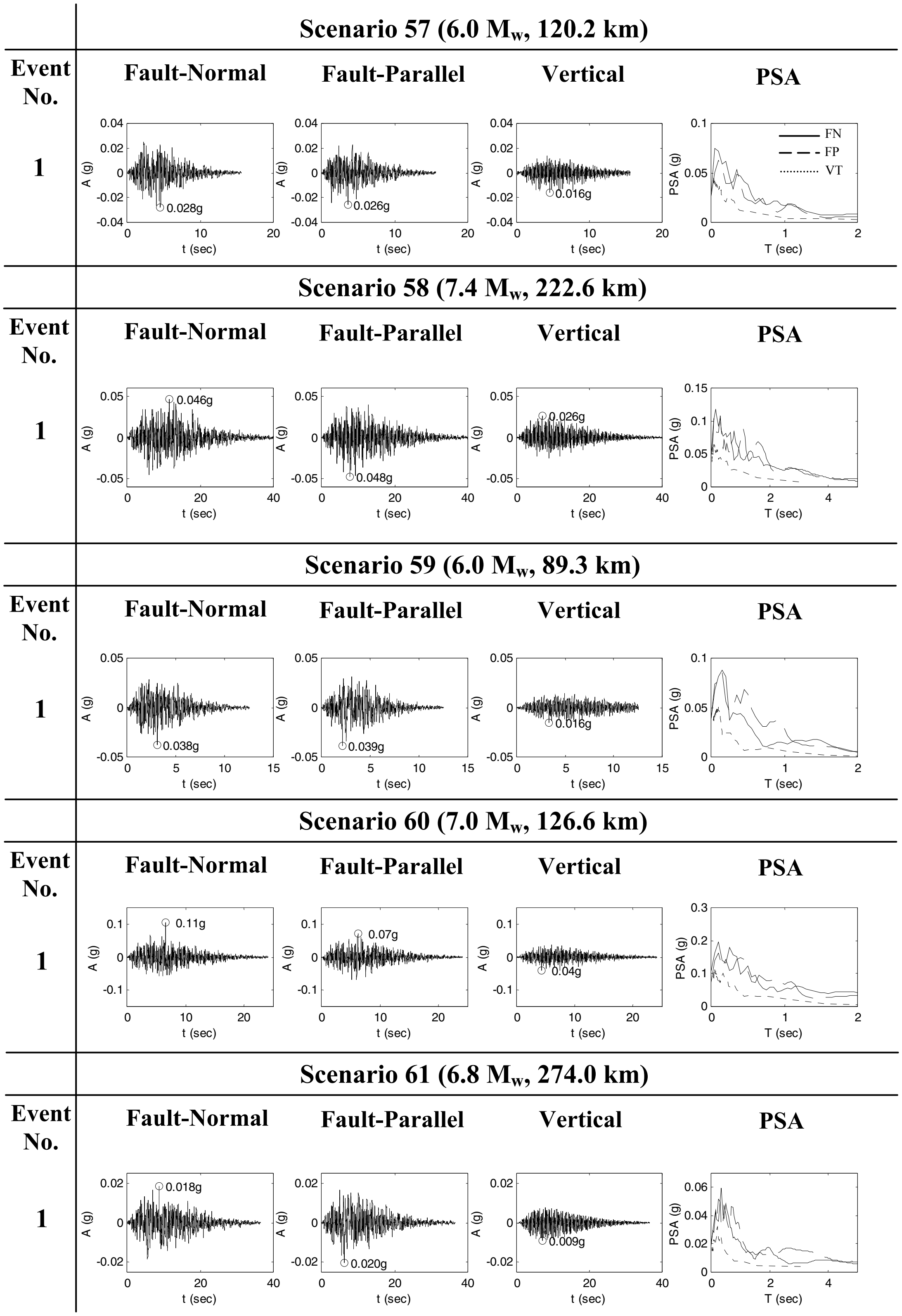
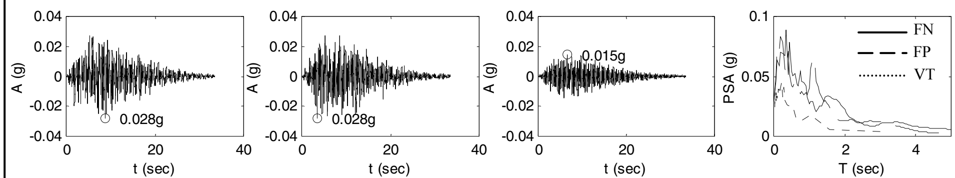


Figure C-2 New York : 5% Probability of Exceedance in 50 Years Long Ensemble (Cont'd)

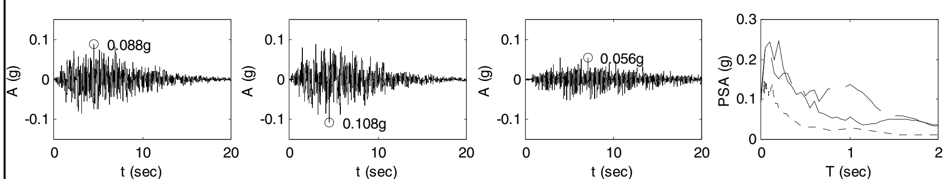
Scenario 62 (7.0 M_w, 222.0 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				



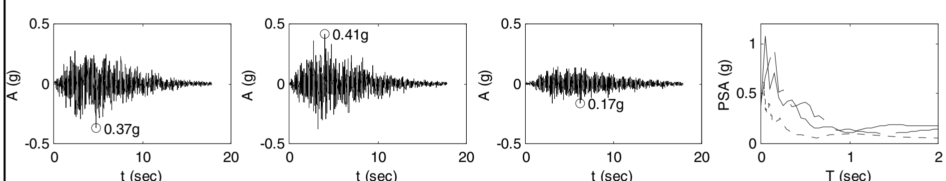
Scenario 63 (7.0 M_w, 86.7 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				



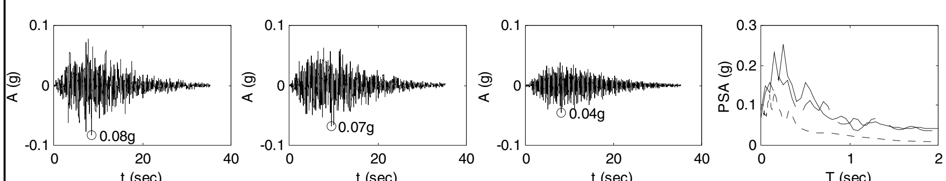
Scenario 64 (7.2 M_w, 35.2 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				



Scenario 65 (7.4 M_w, 171.4 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				



Scenario 66 (6.6 M_w, 15.2 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				

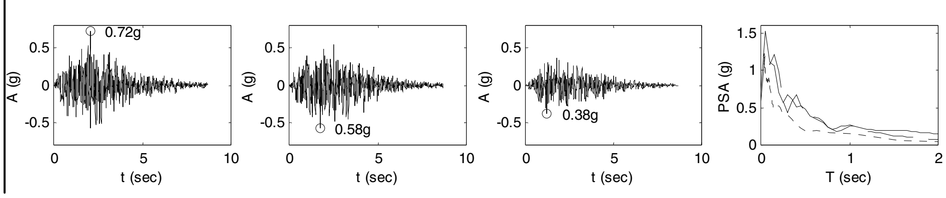
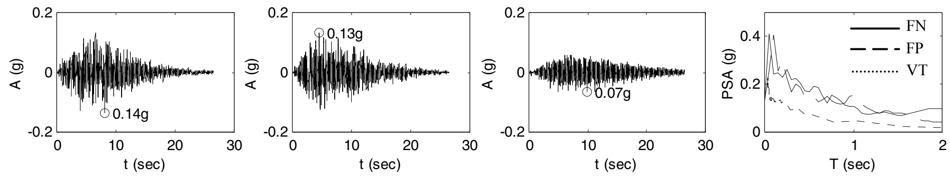


Figure C-2 New York : 5% Probability of Exceedance in 50 Years Long Ensemble (Cont'd)

Scenario 67 (7.4 M_w, 84.7 km)

Event No. | **Fault-Normal** | **Fault-Parallel** | **Vertical** | **PSA**

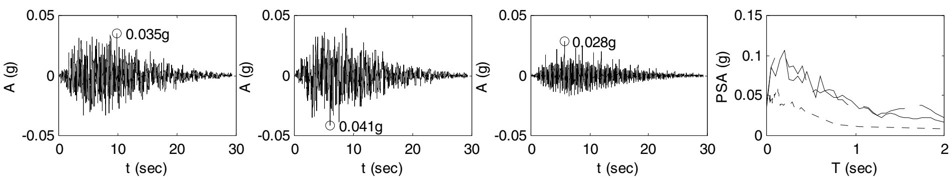
1



Scenario 68 (7.0 M_w, 179.5 km)

Event No. | **Fault-Normal** | **Fault-Parallel** | **Vertical** | **PSA**

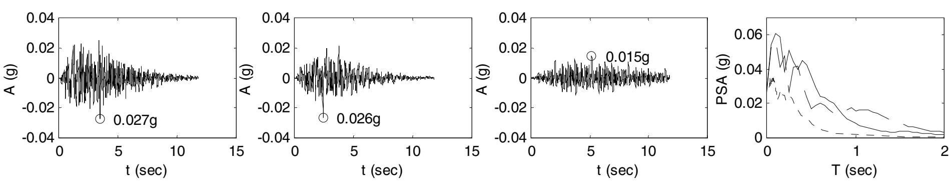
1



Scenario 69 (5.8 M_w, 89.7 km)

Event No. | **Fault-Normal** | **Fault-Parallel** | **Vertical** | **PSA**

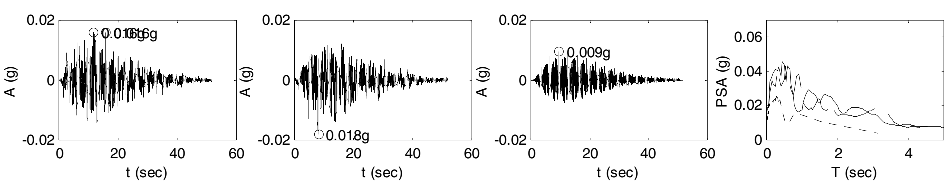
1



Scenario 70 (7.2 M_w, 375.0 km)

Event No. | **Fault-Normal** | **Fault-Parallel** | **Vertical** | **PSA**

1



Scenario 71 (6.6 M_w, 87.1 km)

Event No. | **Fault-Normal** | **Fault-Parallel** | **Vertical** | **PSA**

1

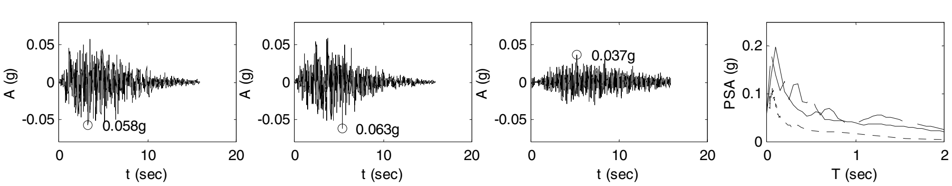


Figure C-2 New York : 5% Probability of Exceedance in 50 Years Long Ensemble (Cont'd)

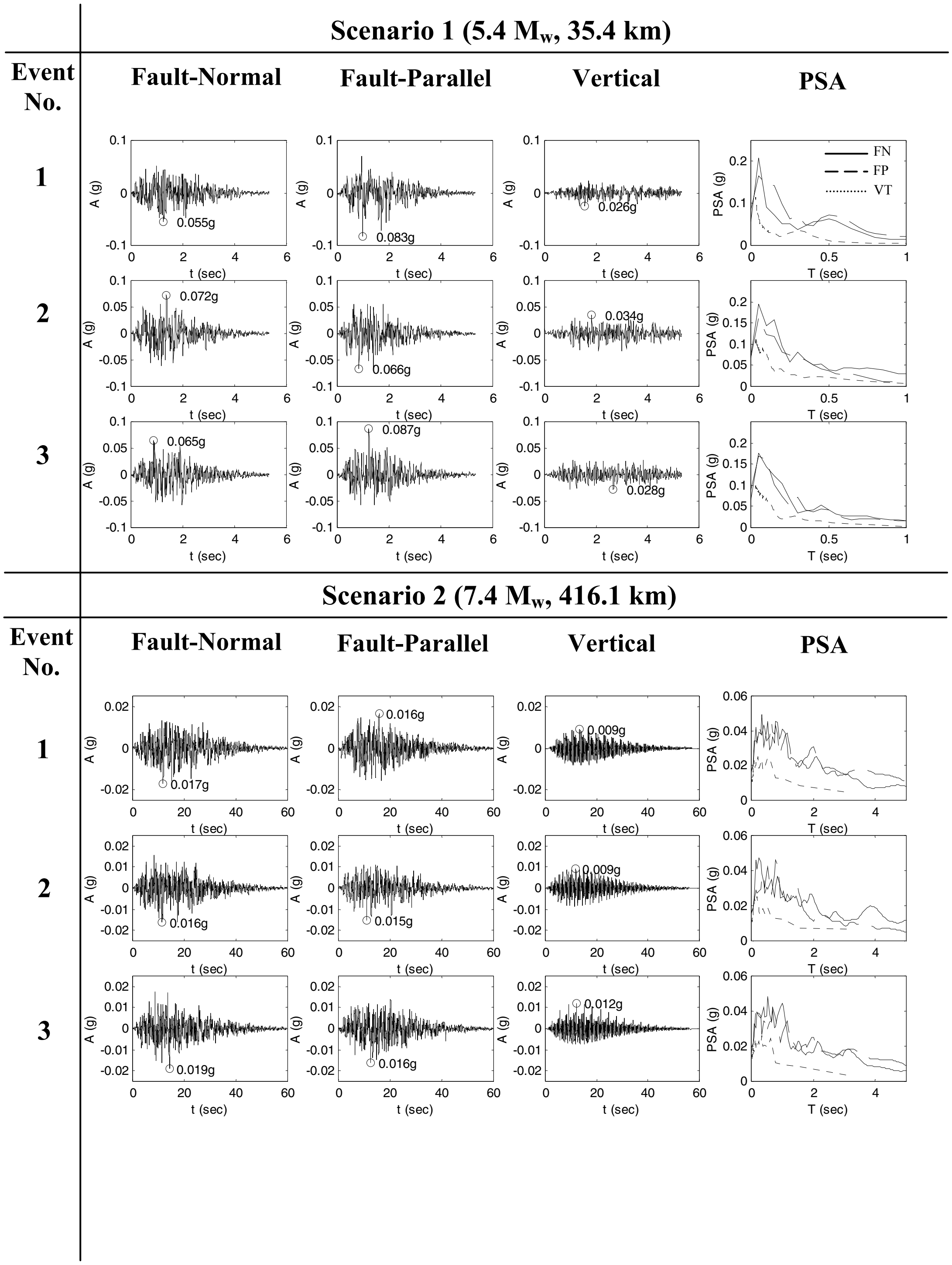


Figure C-3 New York : 10% Probability of Exceedance in 50 Years Long Ensemble

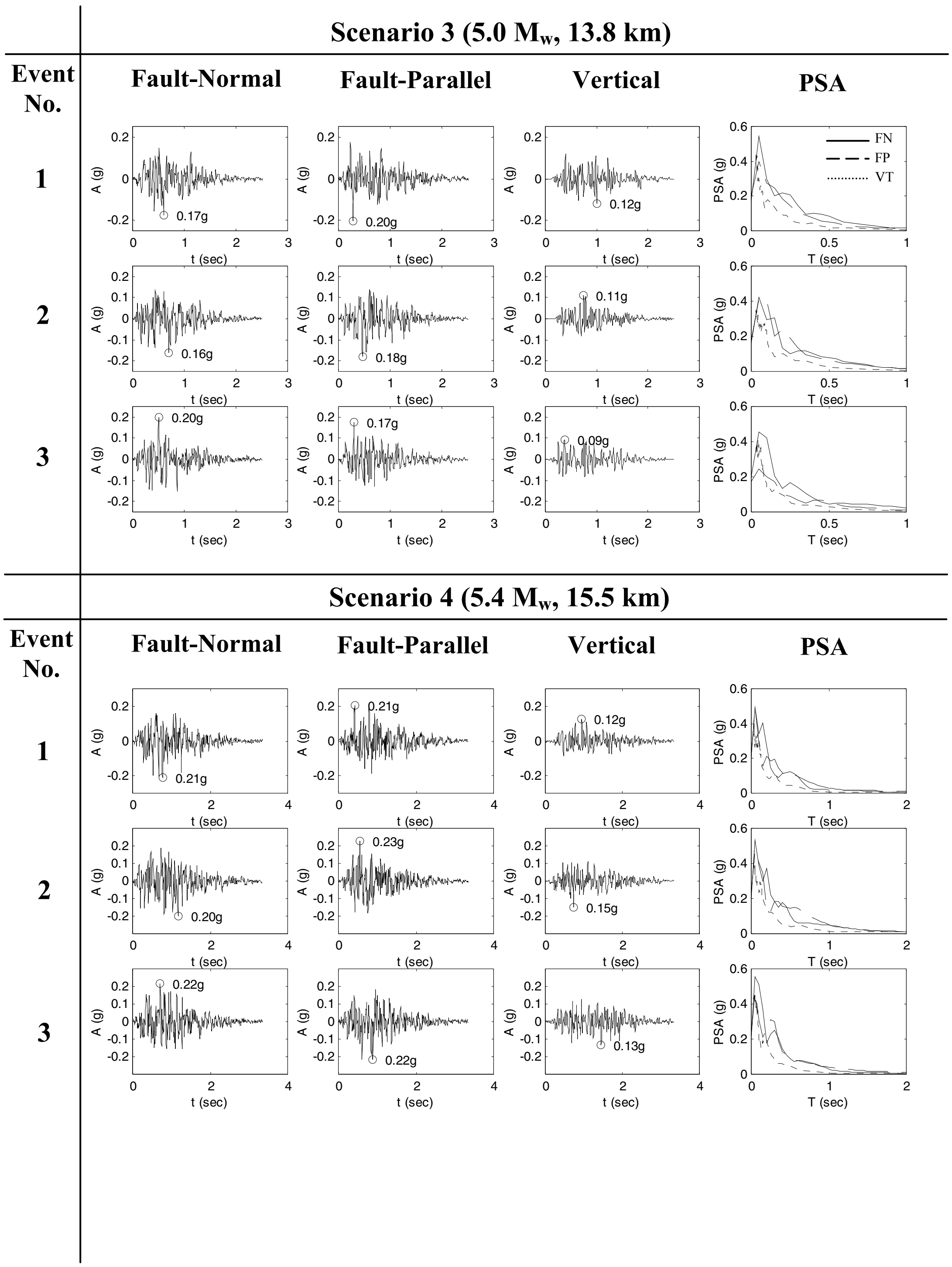


Figure C-3 New York : 10% Probability of Exceedance in 50 Years Long Ensemble (Cont'd)

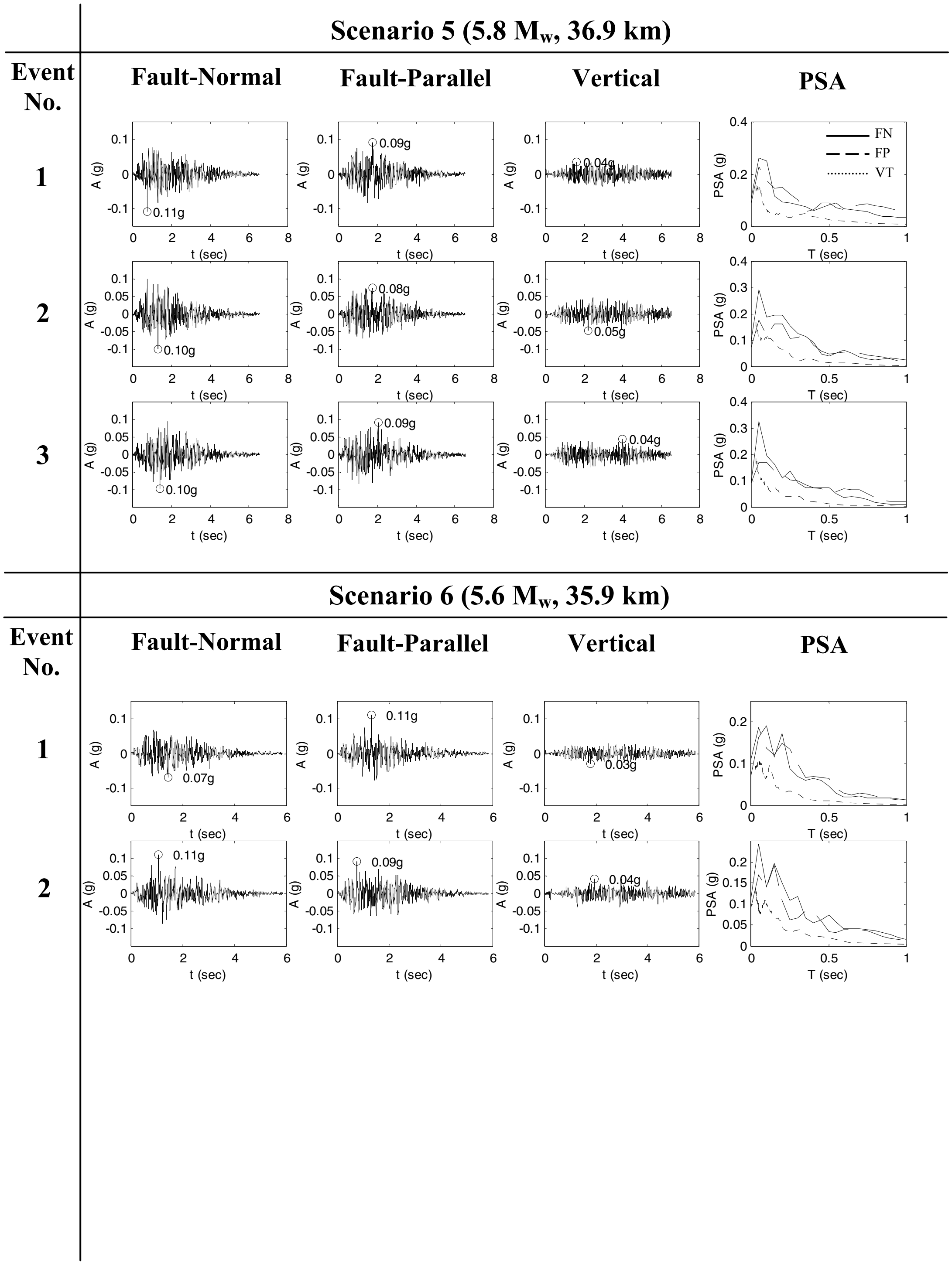


Figure C-3 New York : 10% Probability of Exceedance in 50 Years Long Ensemble (Cont'd)

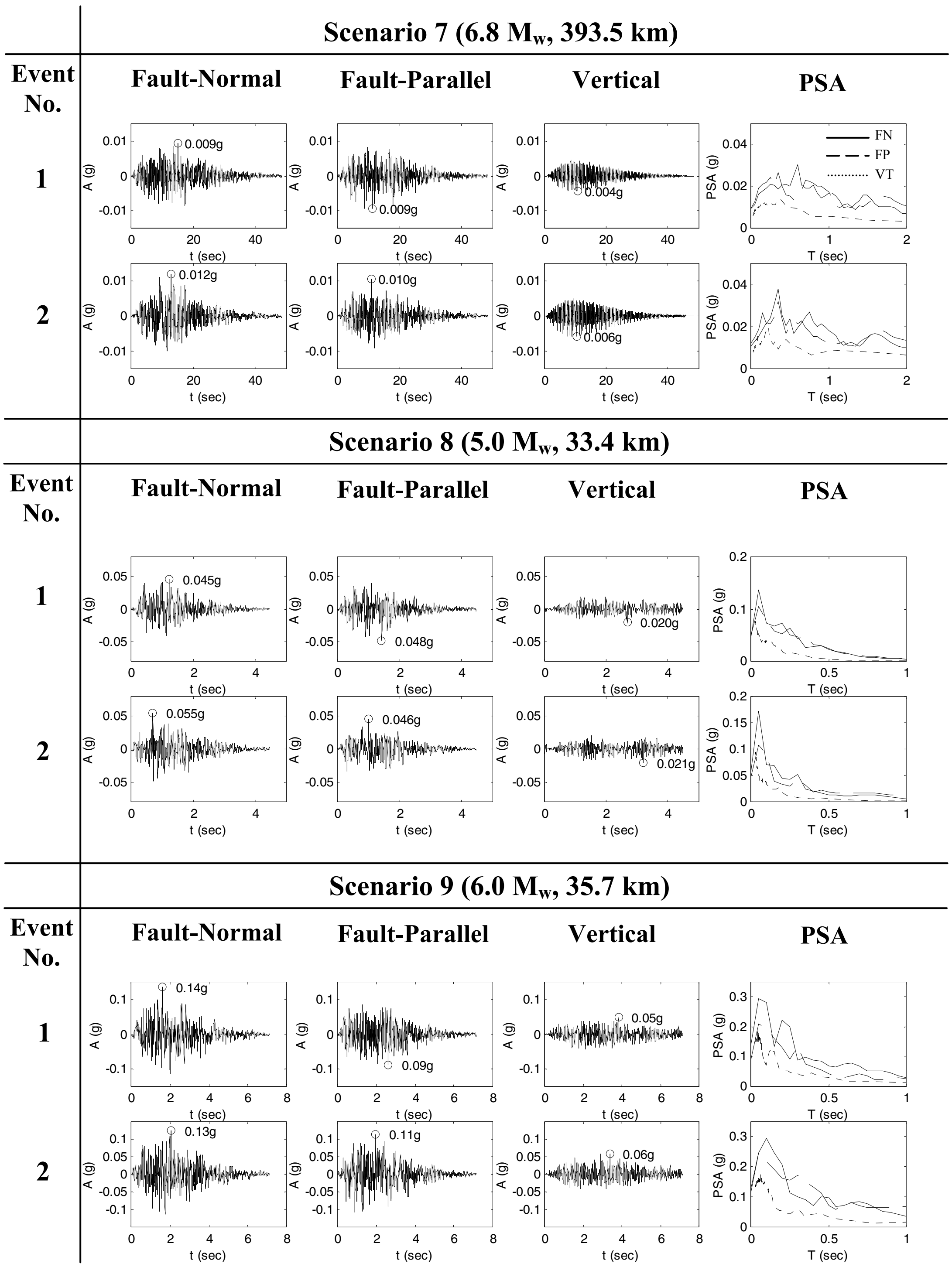


Figure C-3 New York : 10% Probability of Exceedance in 50 Years Long Ensemble (Cont'd)

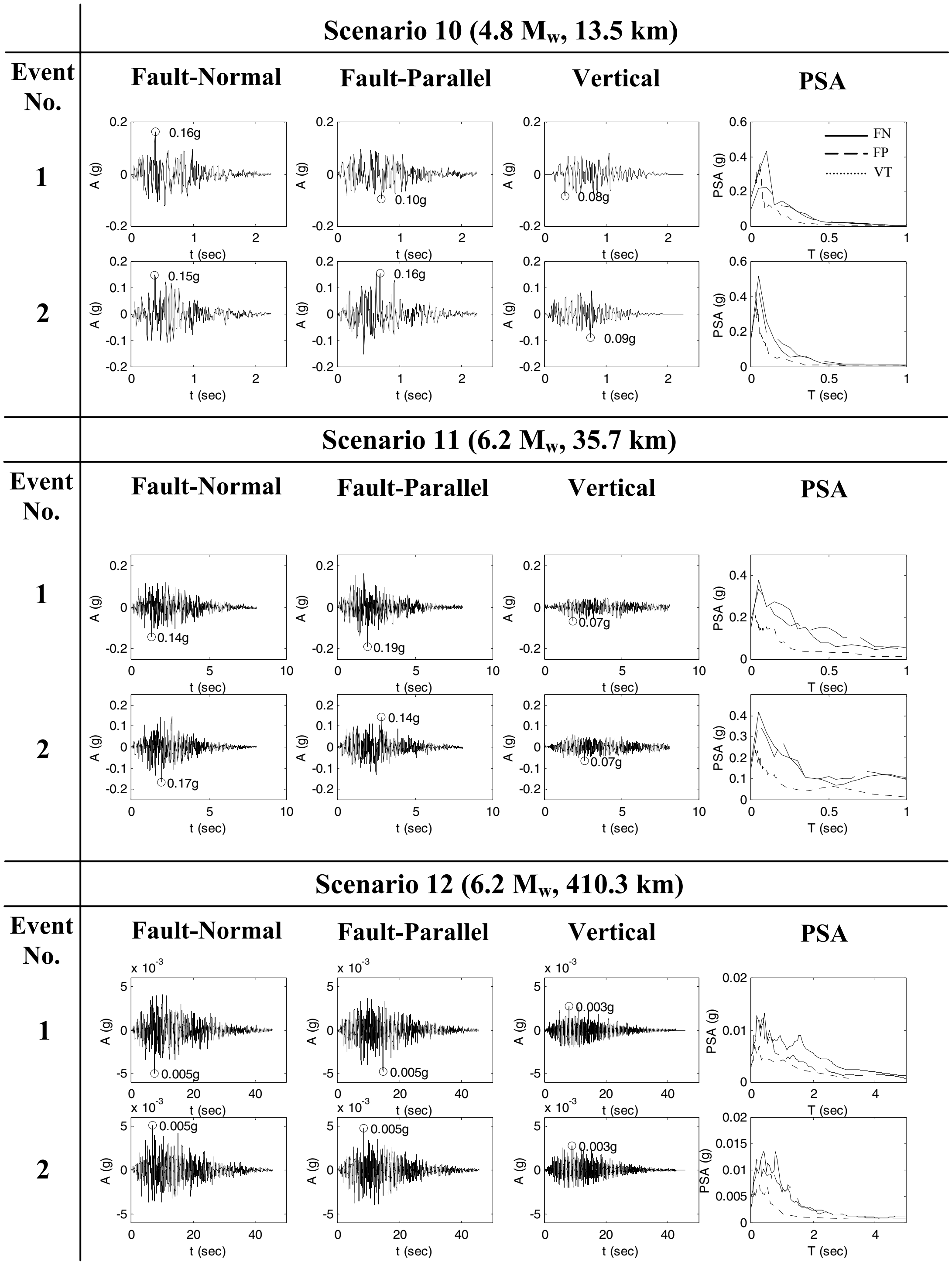


Figure C-3 New York : 10% Probability of Exceedance in 50 Years Long Ensemble (Cont'd)

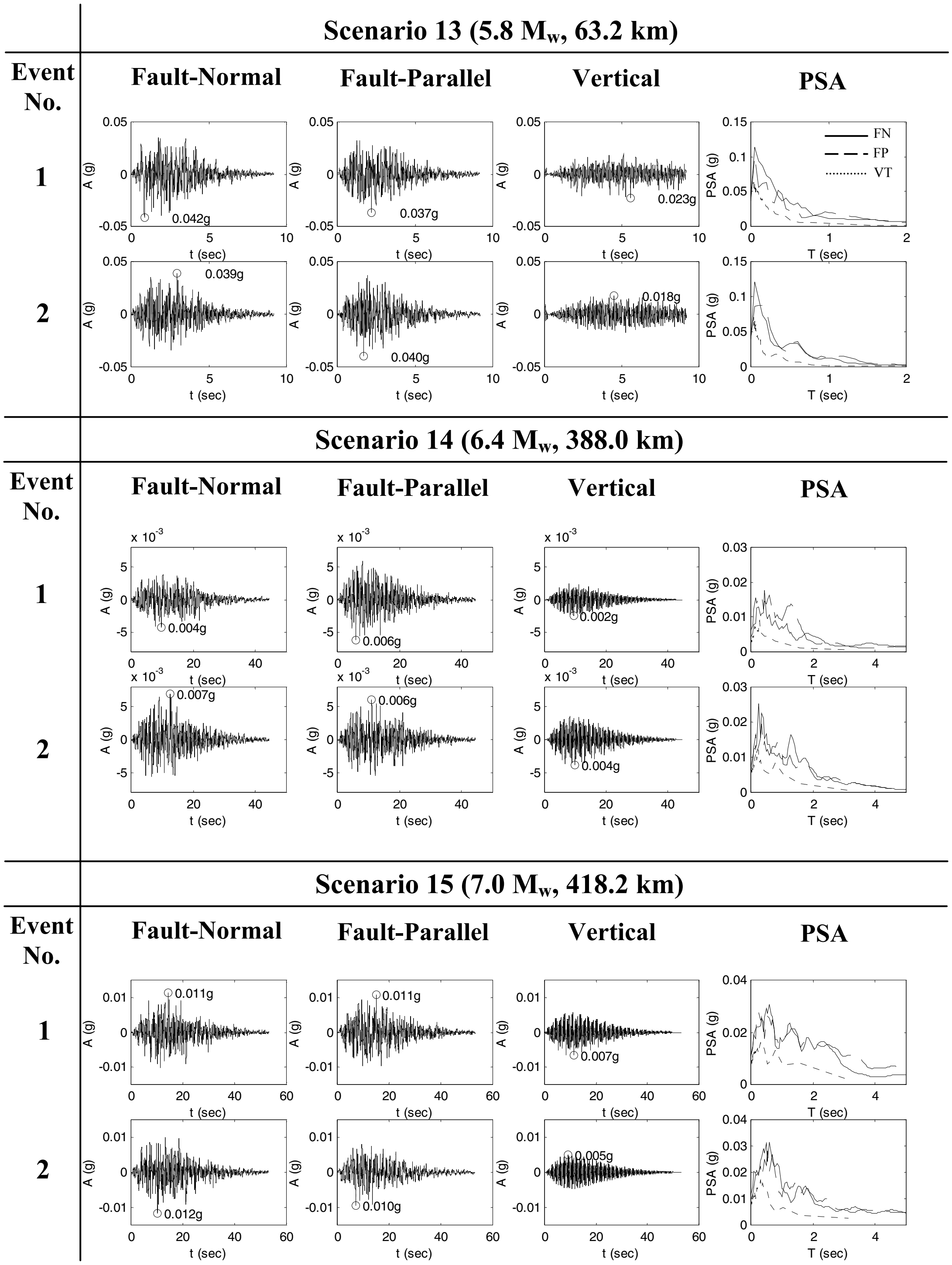


Figure C-3 New York : 10% Probability of Exceedance in 50 Years Long Ensemble (Cont'd)

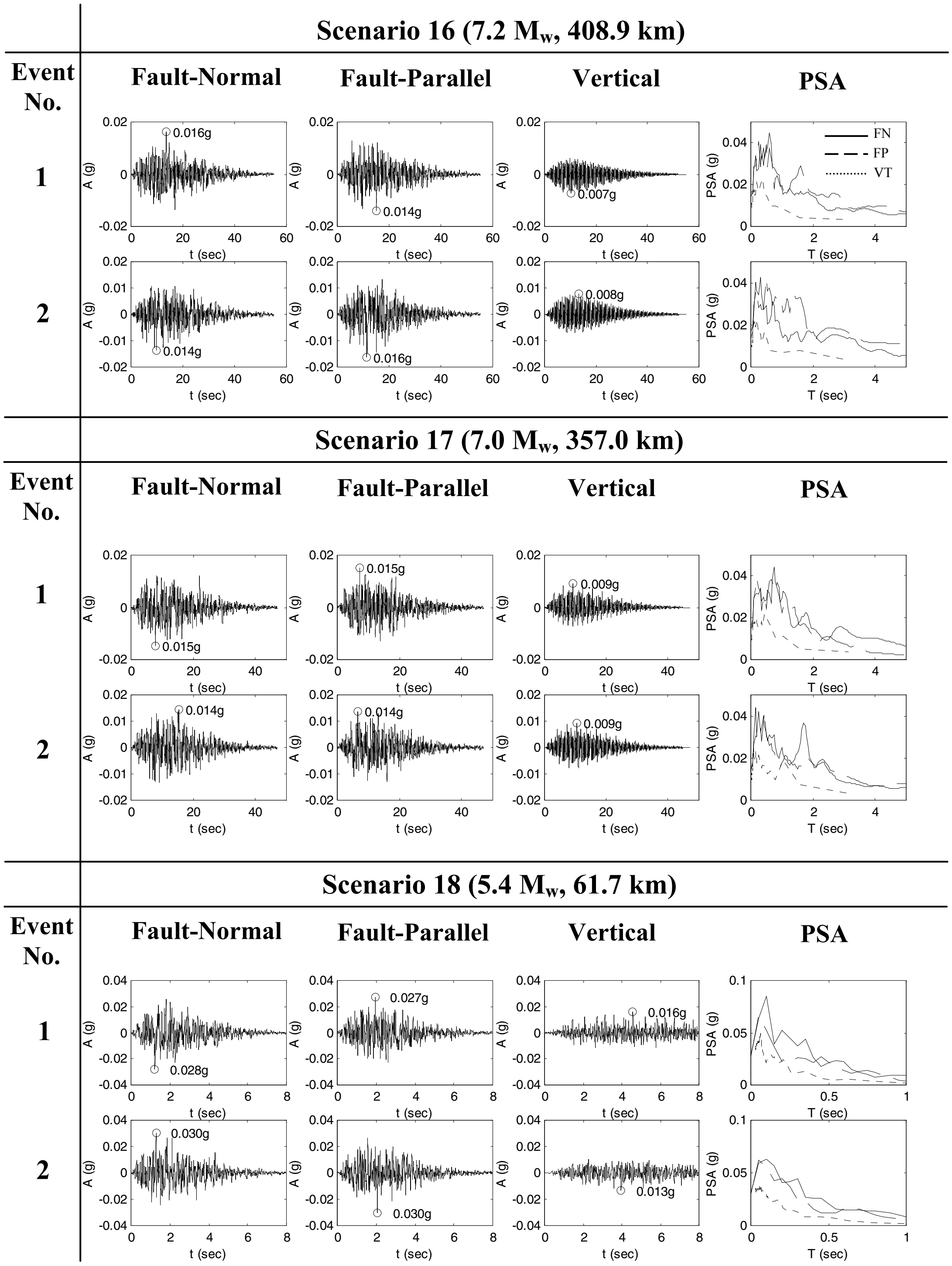


Figure C-3 New York : 10% Probability of Exceedance in 50 Years Long Ensemble (Cont'd)

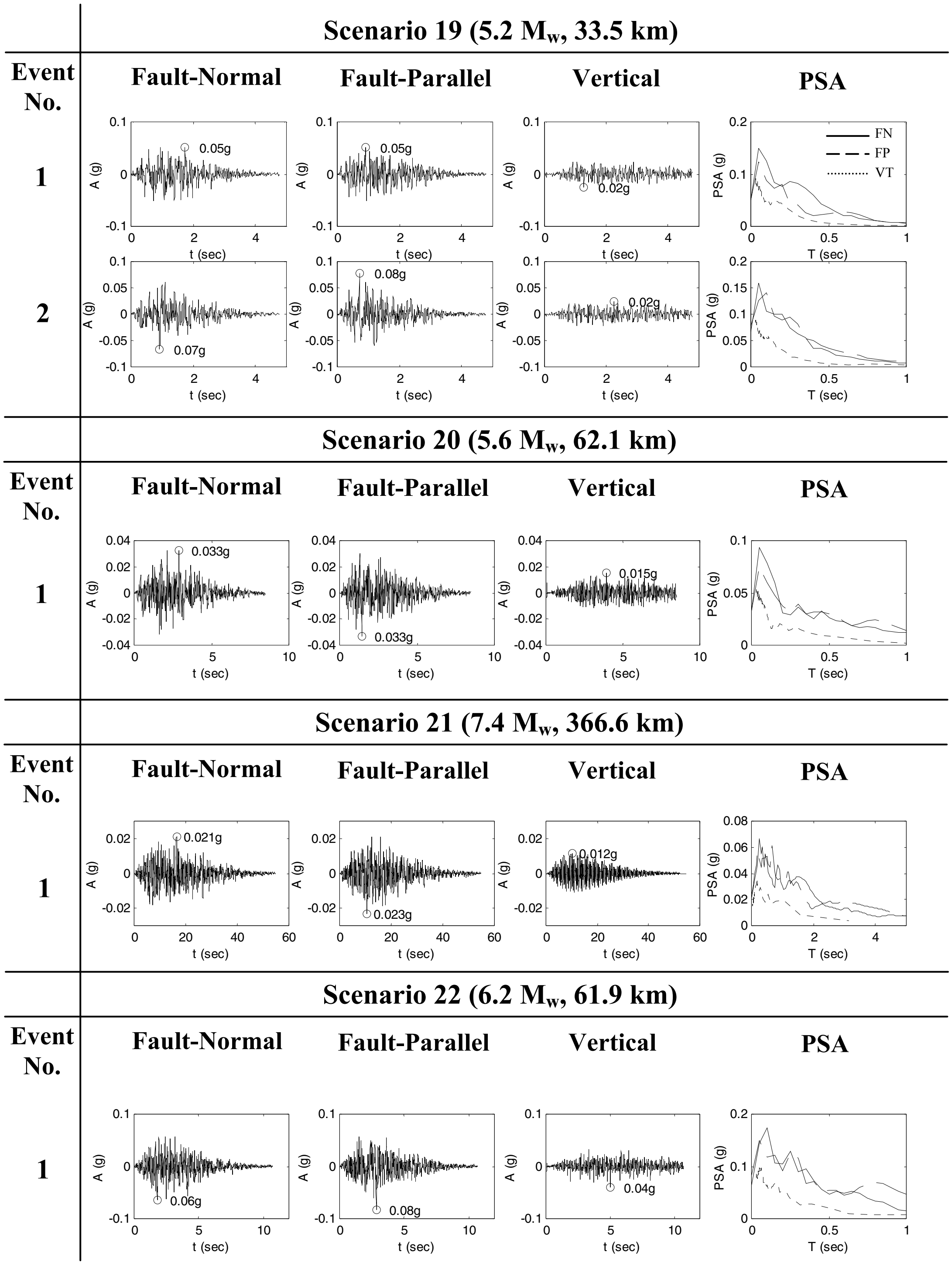
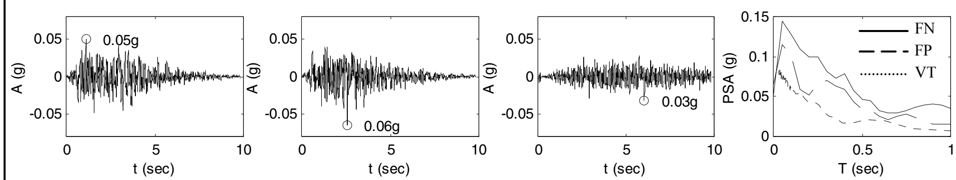


Figure C-3 New York : 10% Probability of Exceedance in 50 Years Long Ensemble (Cont'd)

Scenario 23 (6.0 M_w, 62.5 km)

Event No. | **Fault-Normal** | **Fault-Parallel** | **Vertical** | **PSA**

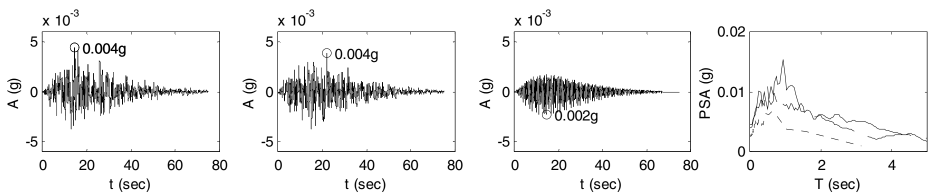
1



Scenario 24 (6.8 M_w, 657.5 km)

Event No. | **Fault-Normal** | **Fault-Parallel** | **Vertical** | **PSA**

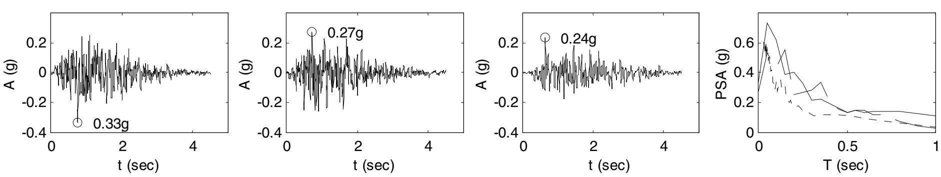
1



Scenario 25 (5.8 M_w, 16.5 km)

Event No. | **Fault-Normal** | **Fault-Parallel** | **Vertical** | **PSA**

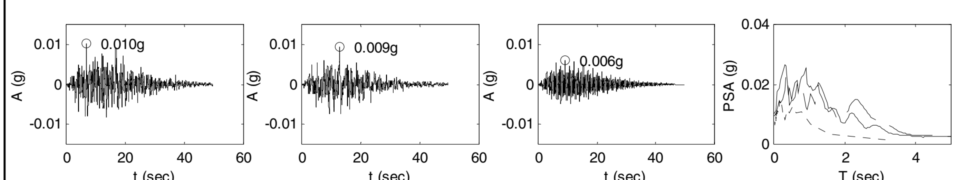
1



Scenario 26 (6.8 M_w, 405.8 km)

Event No. | **Fault-Normal** | **Fault-Parallel** | **Vertical** | **PSA**

1



Scenario 27 (5.6 M_w, 15.4 km)

Event No. | **Fault-Normal** | **Fault-Parallel** | **Vertical** | **PSA**

1

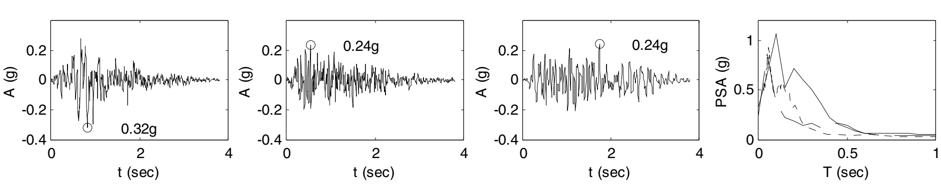
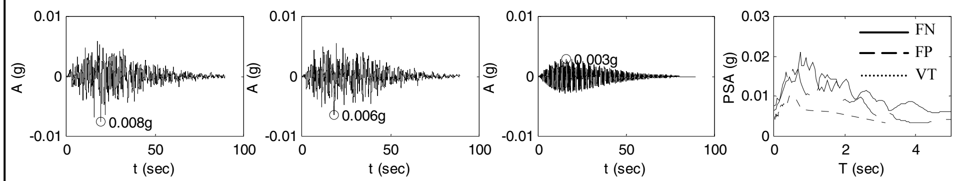


Figure C-3 New York : 10% Probability of Exceedance in 50 Years Long Ensemble (Cont'd)

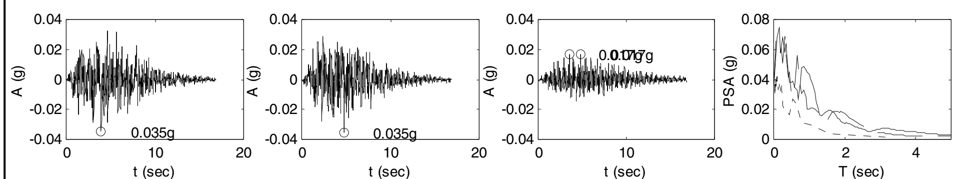
Scenario 28 (7.4 M_w, 714.9 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				



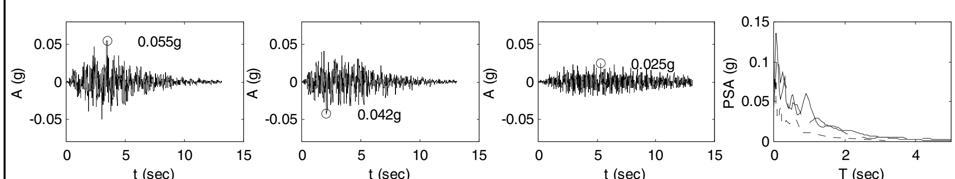
Scenario 29 (6.2 M_w, 123.0 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				



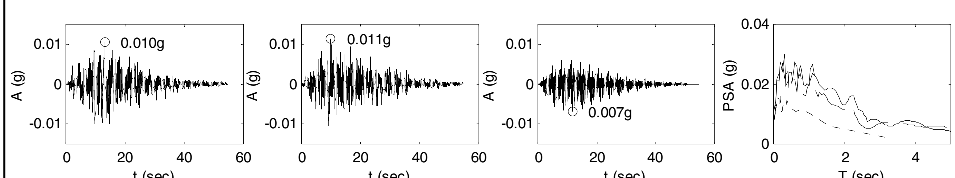
Scenario 30 (6.2 M_w, 86.0 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				



Scenario 31 (7.0 M_w, 432.4 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				



Scenario 32 (6.6 M_w, 407.7 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				

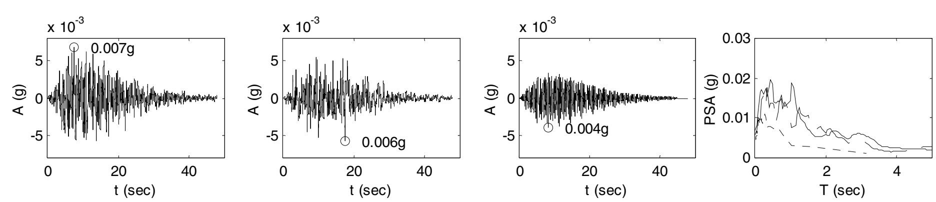
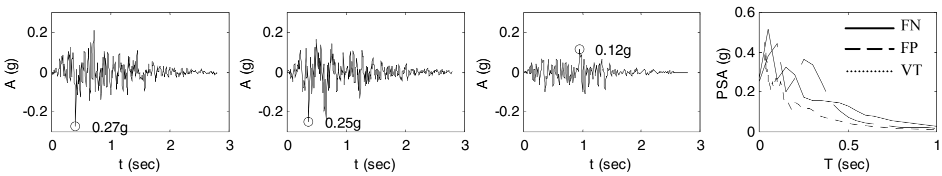


Figure C-3 New York : 10% Probability of Exceedance in 50 Years Long Ensemble (Cont'd)

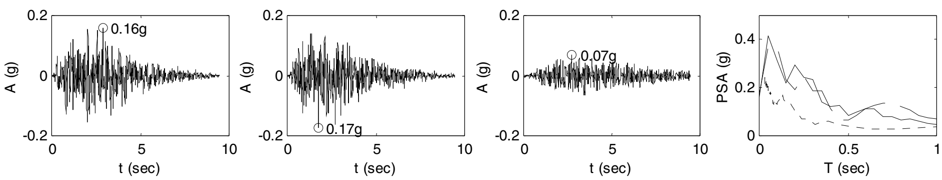
Scenario 33 (5.2 M_w, 13.7 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				



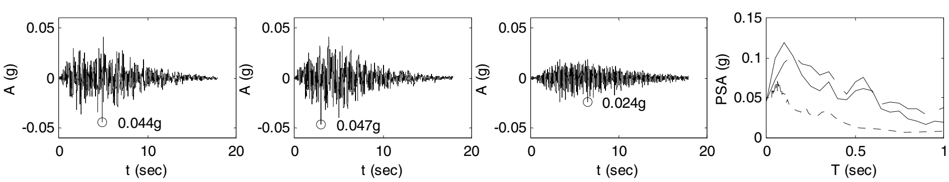
Scenario 34 (6.4 M_w, 37.5 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				



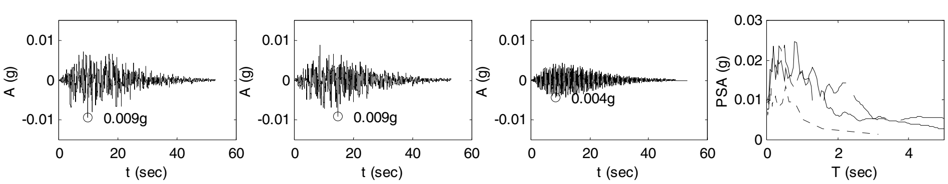
Scenario 35 (6.4 M_w, 121.9 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				



Scenario 36 (6.8 M_w, 440.1 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				



Scenario 37 (6.8 M_w, 37.1 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				

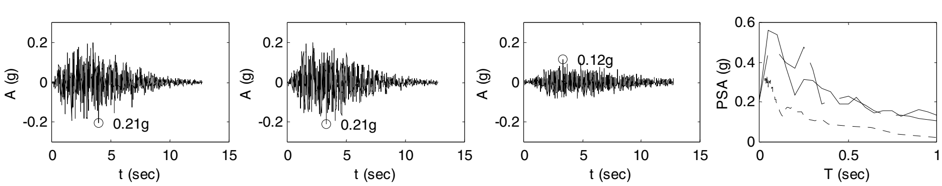
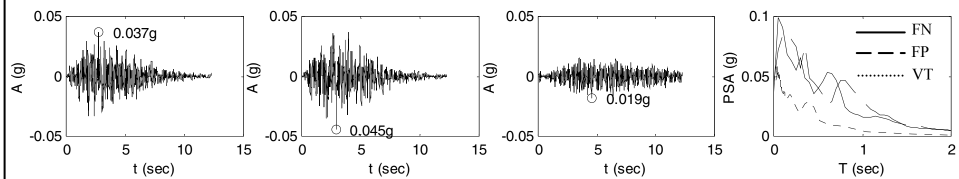


Figure C-3 New York : 10% Probability of Exceedance in 50 Years Long Ensemble (Cont'd)

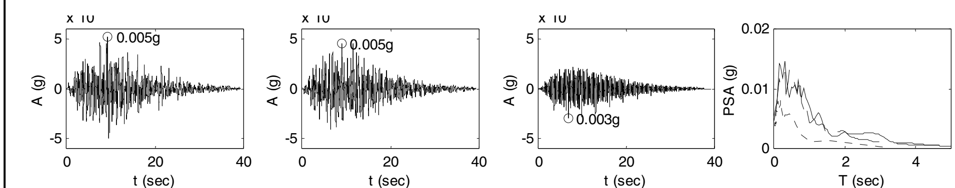
Scenario 38 (6.0 M_w, 86.8 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				



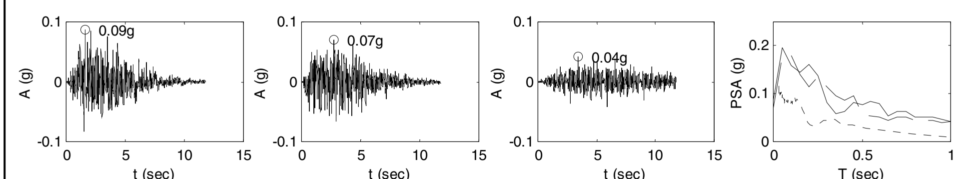
Scenario 39 (6.0 M_w, 356.4 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				



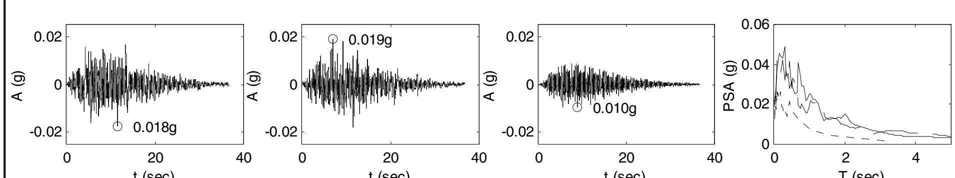
Scenario 40 (6.4 M_w, 60.7 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				



Scenario 41 (6.8 M_w, 276.4 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				



Scenario 42 (6.4 M_w, 85.1 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				

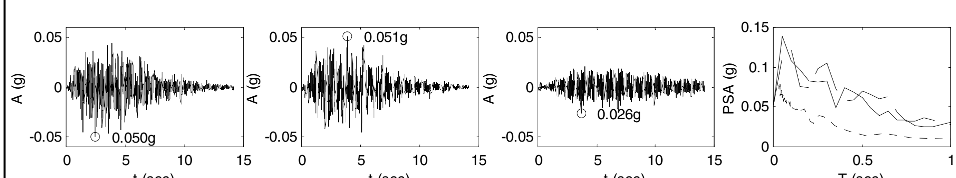
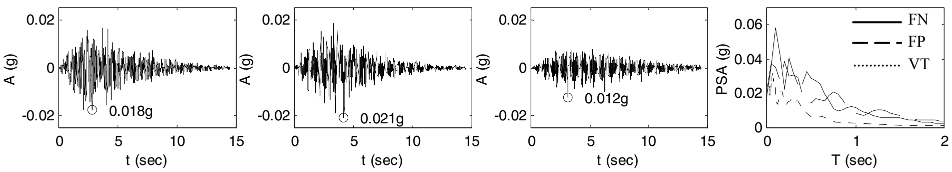


Figure C-3 New York : 10% Probability of Exceedance in 50 Years Long Ensemble (Cont'd)

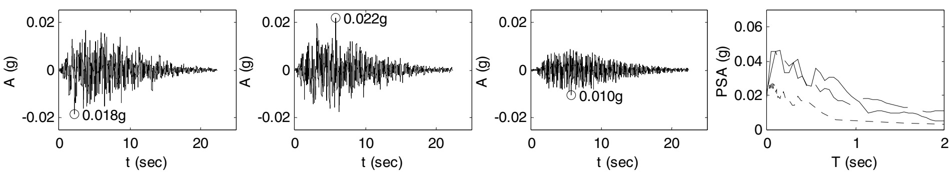
Scenario 43 (5.6 M_w, 122.0 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				



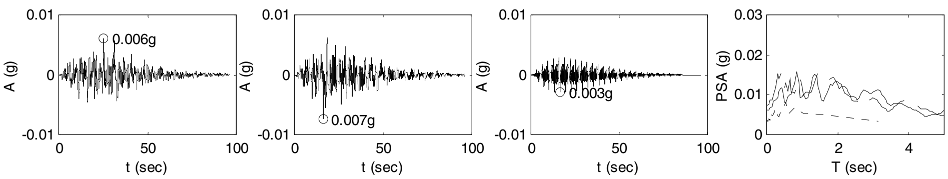
Scenario 44 (6.2 M_w, 177.4 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				



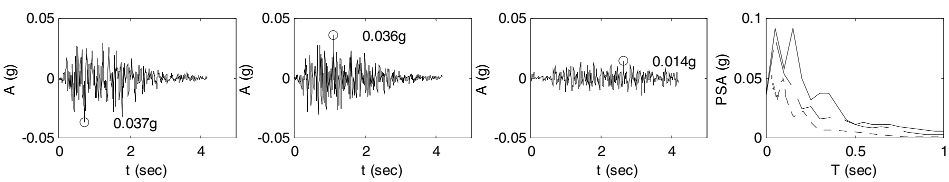
Scenario 45 (7.4 M_w, 780.9 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				



Scenario 46 (4.8 M_w, 32.8 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				



Scenario 47 (5.8 M_w, 88.6 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				

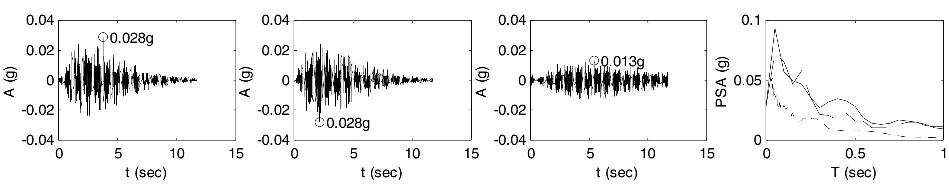
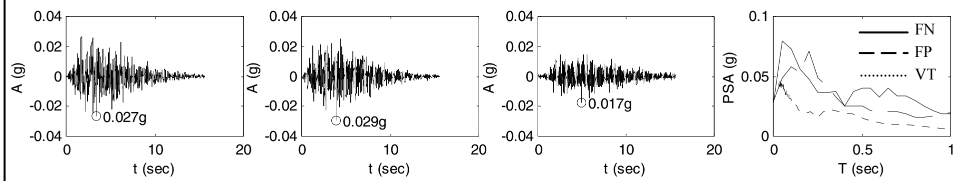
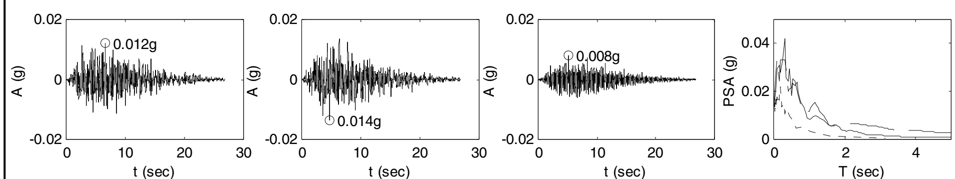
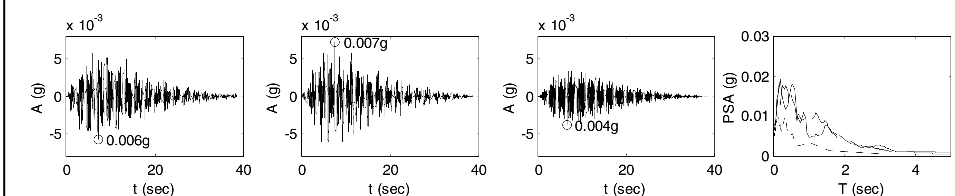
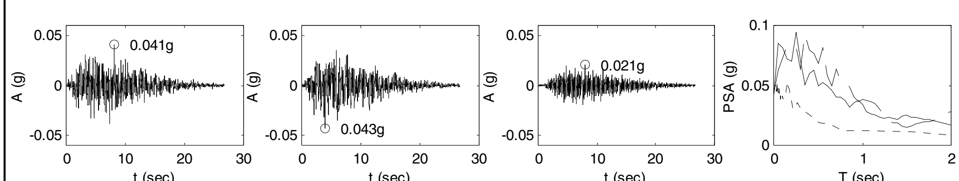


Figure C-3 New York : 10% Probability of Exceedance in 50 Years Long Ensemble (Cont'd)

Event No.	Scenario 48 (6.0 M_w, 120.0 km)
	Fault-Normal, Fault-Parallel, Vertical, PSA
1	

Event No.	Scenario 49 (6.2 M_w, 222.5 km)
	Fault-Normal, Fault-Parallel, Vertical, PSA
1	

Event No.	Scenario 50 (6.2 M_w, 339.3 km)
	Fault-Normal, Fault-Parallel, Vertical, PSA
1	

Event No.	Scenario 51 (6.8 M_w, 177.1 km)
	Fault-Normal, Fault-Parallel, Vertical, PSA
1	

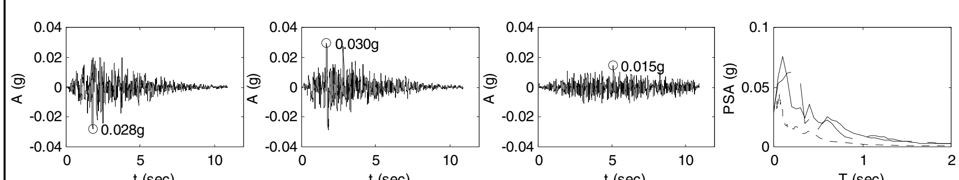
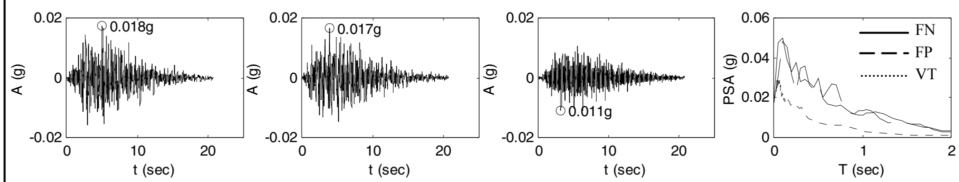
Event No.	Scenario 52 (5.6 M_w, 86.9 km)
	Fault-Normal, Fault-Parallel, Vertical, PSA
1	

Figure C-3 New York : 10% Probability of Exceedance in 50 Years Long Ensemble (Cont'd)

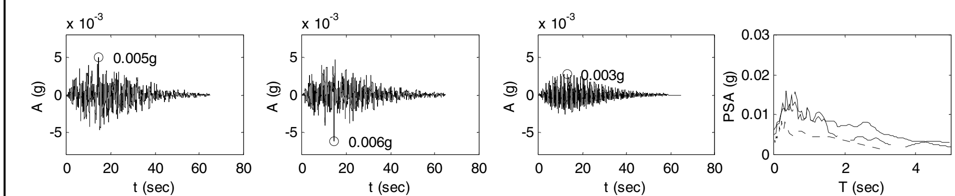
Scenario 53 (6.0 M_w, 171.0 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				



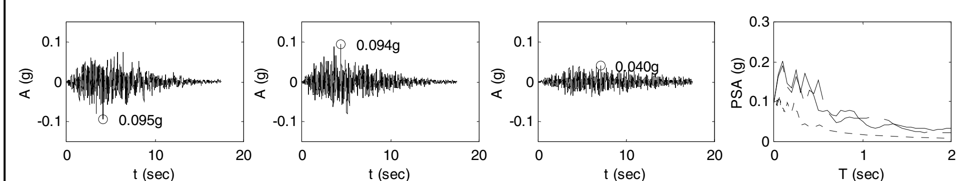
Scenario 54 (6.8 M_w, 557.8 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				



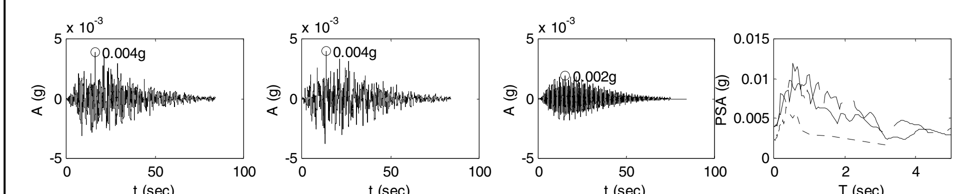
Scenario 55 (6.8 M_w, 85.0 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				



Scenario 56 (7.0 M_w, 726.8 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				



Scenario 57 (5.4 M_w, 86.7 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				

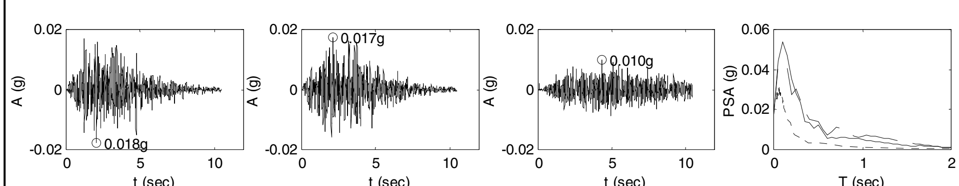
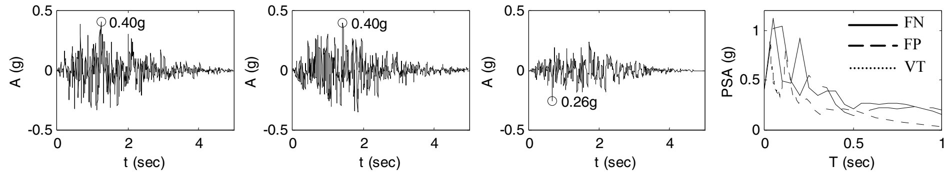


Figure C-3 New York : 10% Probability of Exceedance in 50 Years Long Ensemble (Cont'd)

Scenario 58 (6.0 M_w, 13.8 km)

Event No. | **Fault-Normal** | **Fault-Parallel** | **Vertical** | **PSA**

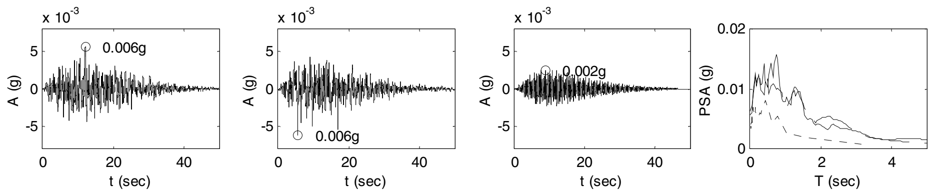
1



Scenario 59 (6.4 M_w, 439.1 km)

Event No. | **Fault-Normal** | **Fault-Parallel** | **Vertical** | **PSA**

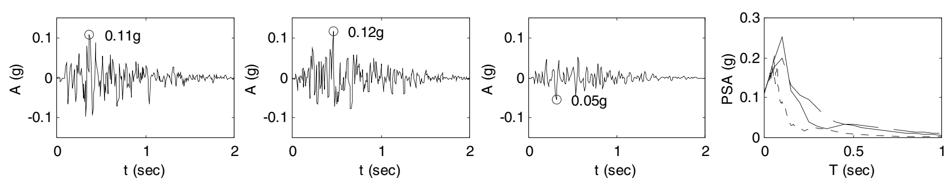
1



Scenario 60 (4.6 M_w, 13.9 km)

Event No. | **Fault-Normal** | **Fault-Parallel** | **Vertical** | **PSA**

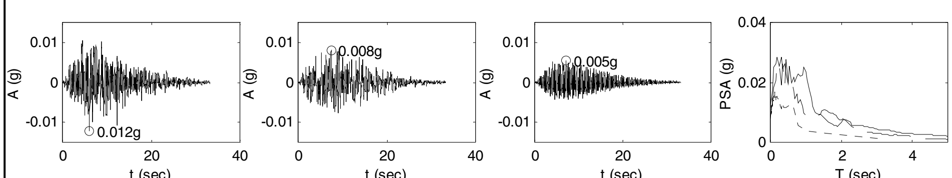
1



Scenario 61 (6.4 M_w, 275.7 km)

Event No. | **Fault-Normal** | **Fault-Parallel** | **Vertical** | **PSA**

1



Scenario 62 (6.6 M_w, 36.6 km)

Event No. | **Fault-Normal** | **Fault-Parallel** | **Vertical** | **PSA**

1

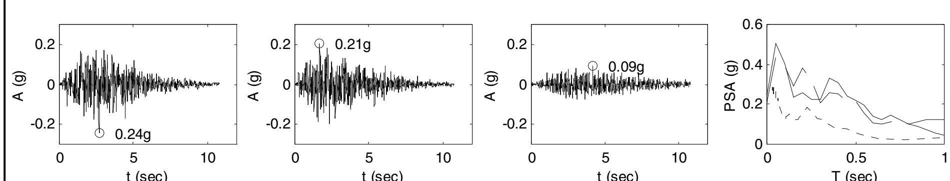


Figure C-3 New York : 10% Probability of Exceedance in 50 Years Long Ensemble (Cont'd)

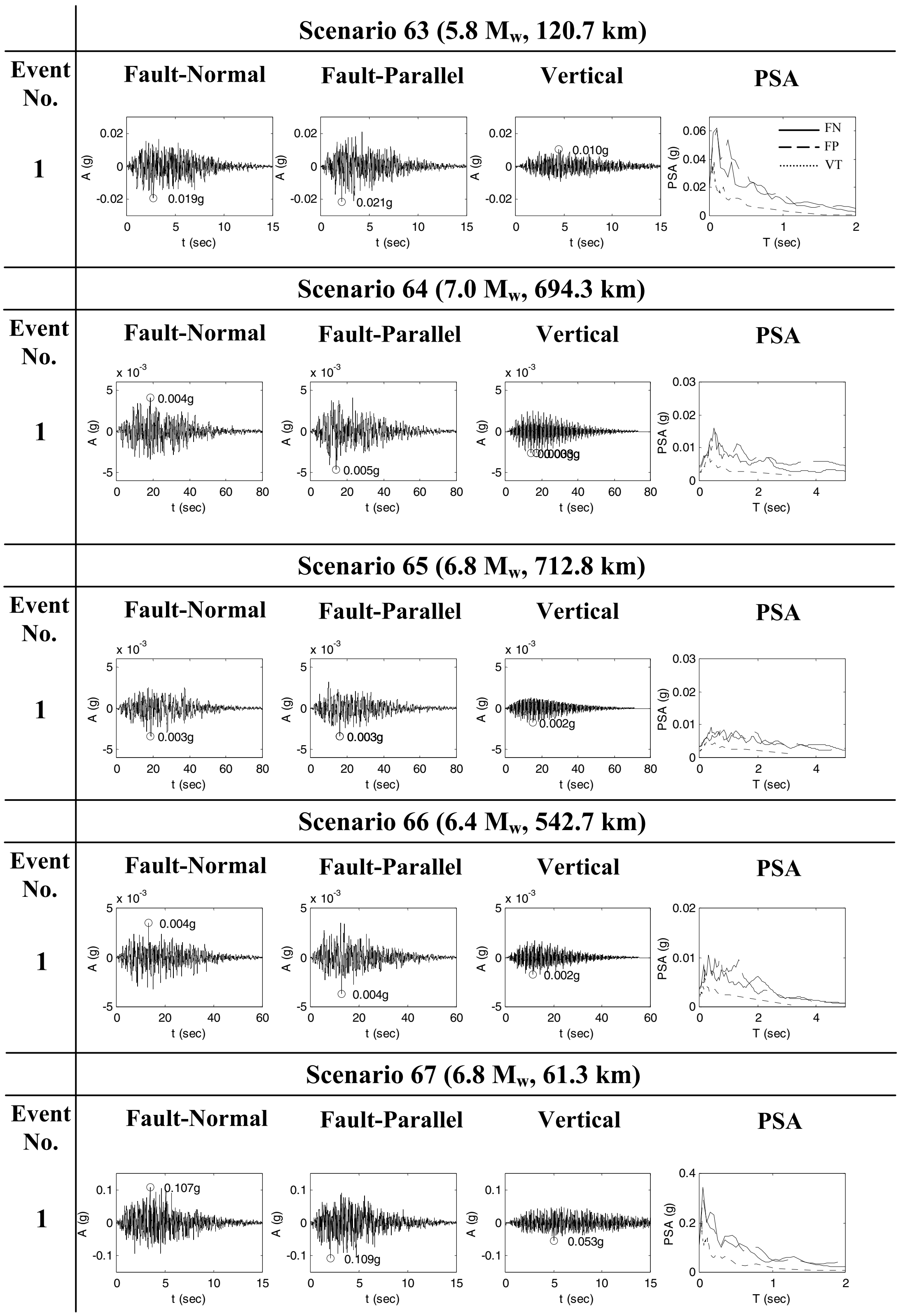
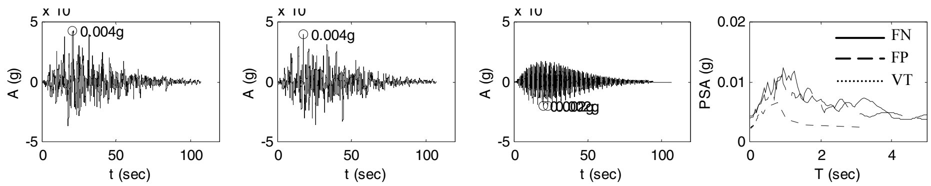


Figure C-3 New York : 10% Probability of Exceedance in 50 Years Long Ensemble (Cont'd)

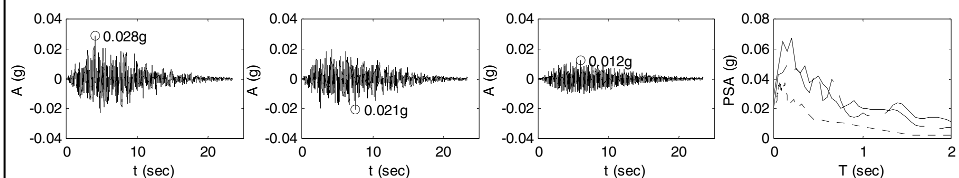
Scenario 68 (7.3 M_w, 911.1 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				



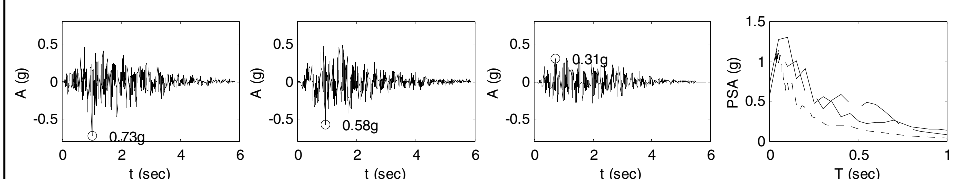
Scenario 69 (6.4 M_w, 177.0 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				



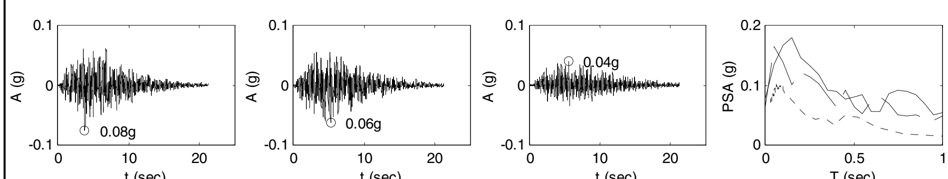
Scenario 70 (6.2 M_w, 13.4 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				



Scenario 71 (6.8 M_w, 122.5 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				



Scenario 72 (7.4 M_w, 633.9 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				

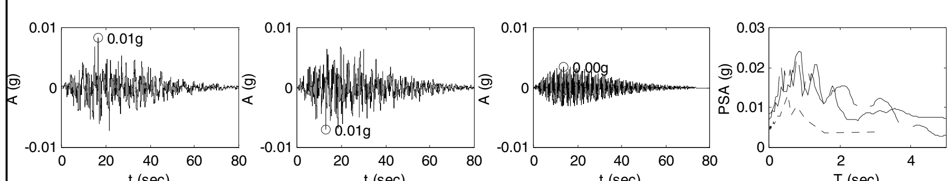
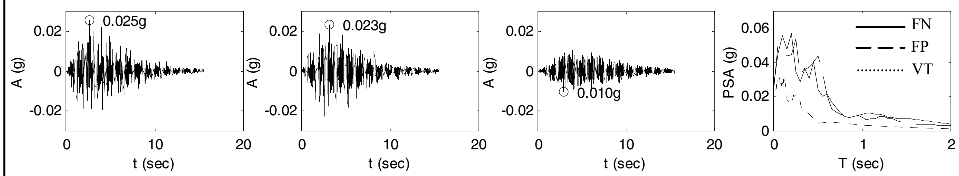


Figure C-3 New York : 10% Probability of Exceedance in 50 Years Long Ensemble (Cont'd)

Scenario 73 (5.8 M_w, 126.5 km)

Event No. | **Fault-Normal** | **Fault-Parallel** | **Vertical** | **PSA**

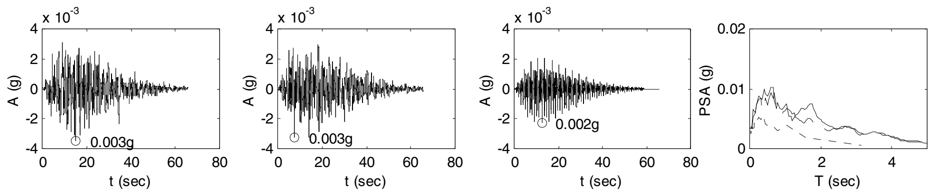
1



Scenario 74 (6.6 M_w, 585.5 km)

Event No. | **Fault-Normal** | **Fault-Parallel** | **Vertical** | **PSA**

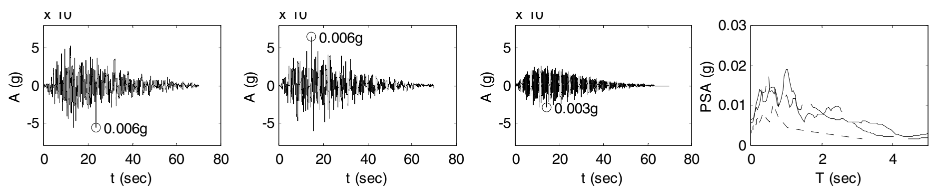
1



Scenario 75 (7.0 M_w, 586.7 km)

Event No. | **Fault-Normal** | **Fault-Parallel** | **Vertical** | **PSA**

1



Scenario 76 (6.6 M_w, 63.5 km)

Event No. | **Fault-Normal** | **Fault-Parallel** | **Vertical** | **PSA**

1

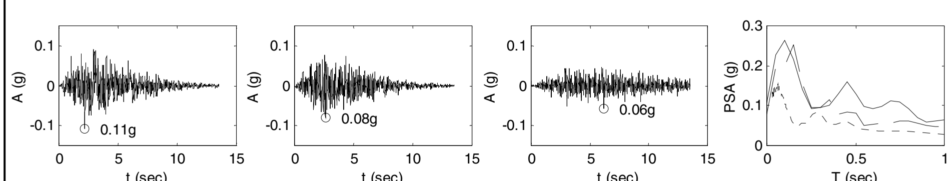


Figure C-3 New York : 10% Probability of Exceedance in 50 Years Long Ensemble (Cont'd)

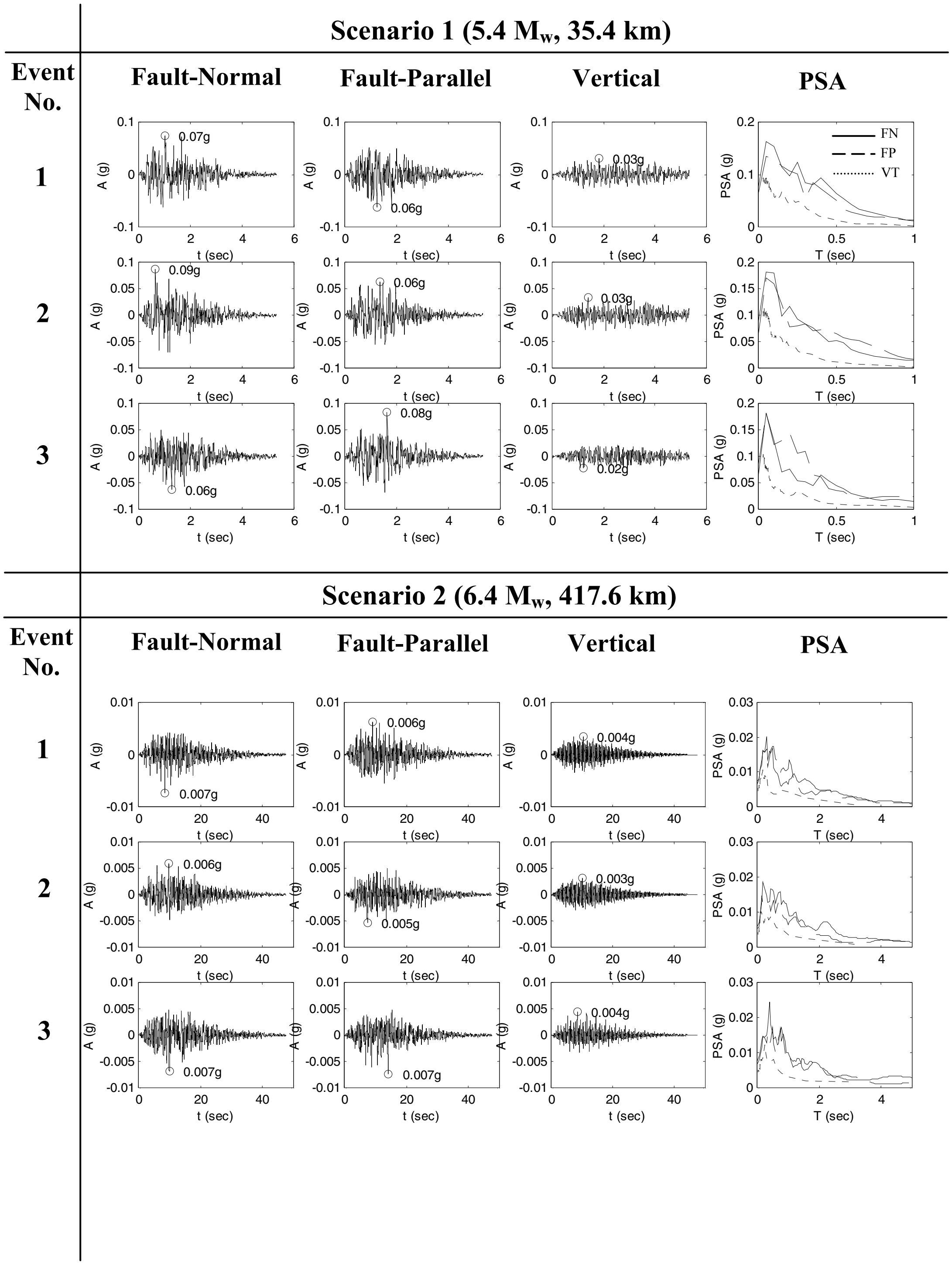


Figure C-4 New York : 20% Probability of Exceedance in 50 Years Long Ensemble

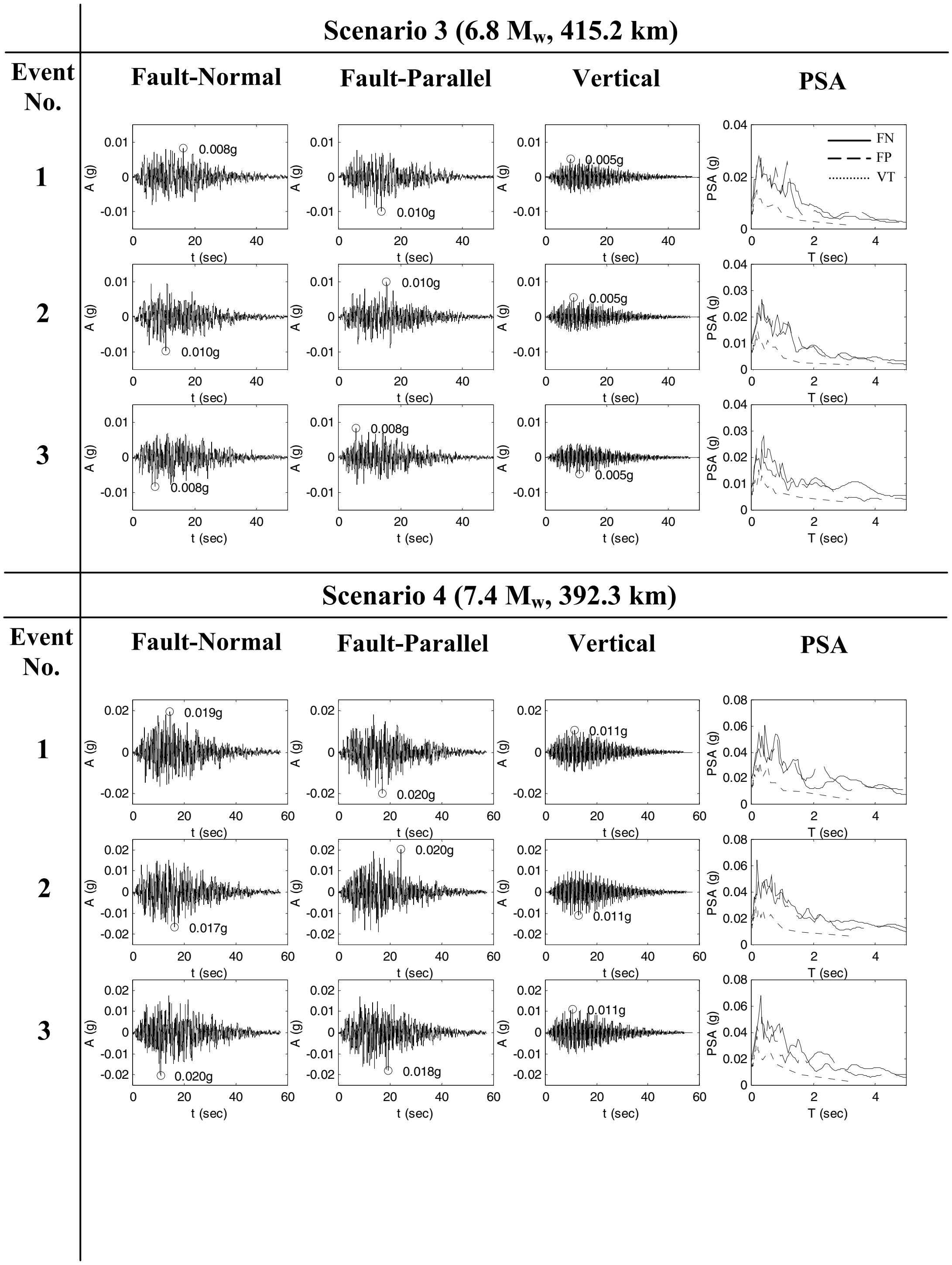


Figure C-4 New York : 20% Probability of Exceedance in 50 Years Long Ensemble (Cont'd)

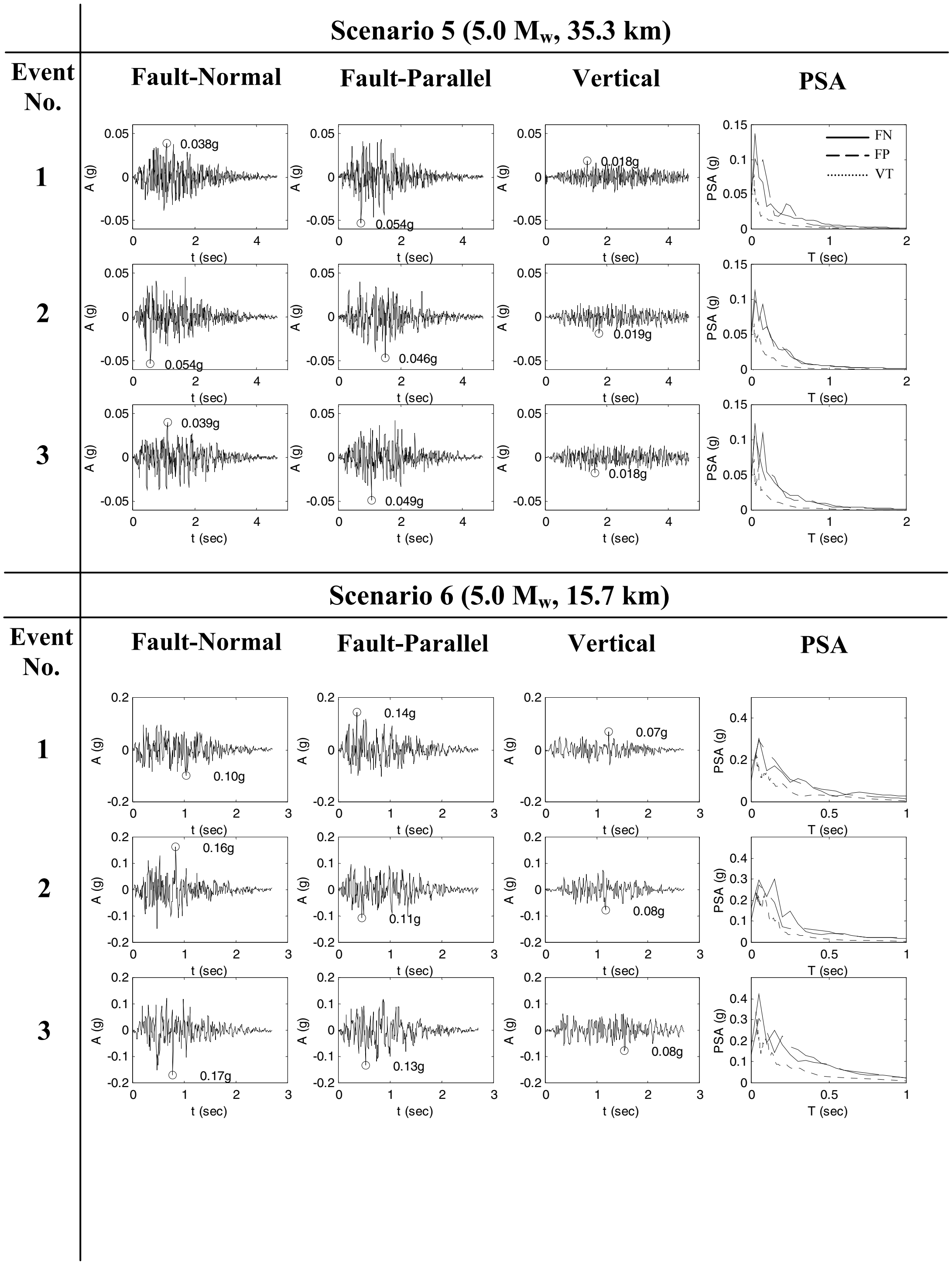


Figure C-4 New York : 20% Probability of Exceedance in 50 Years Long Ensemble (Cont'd)

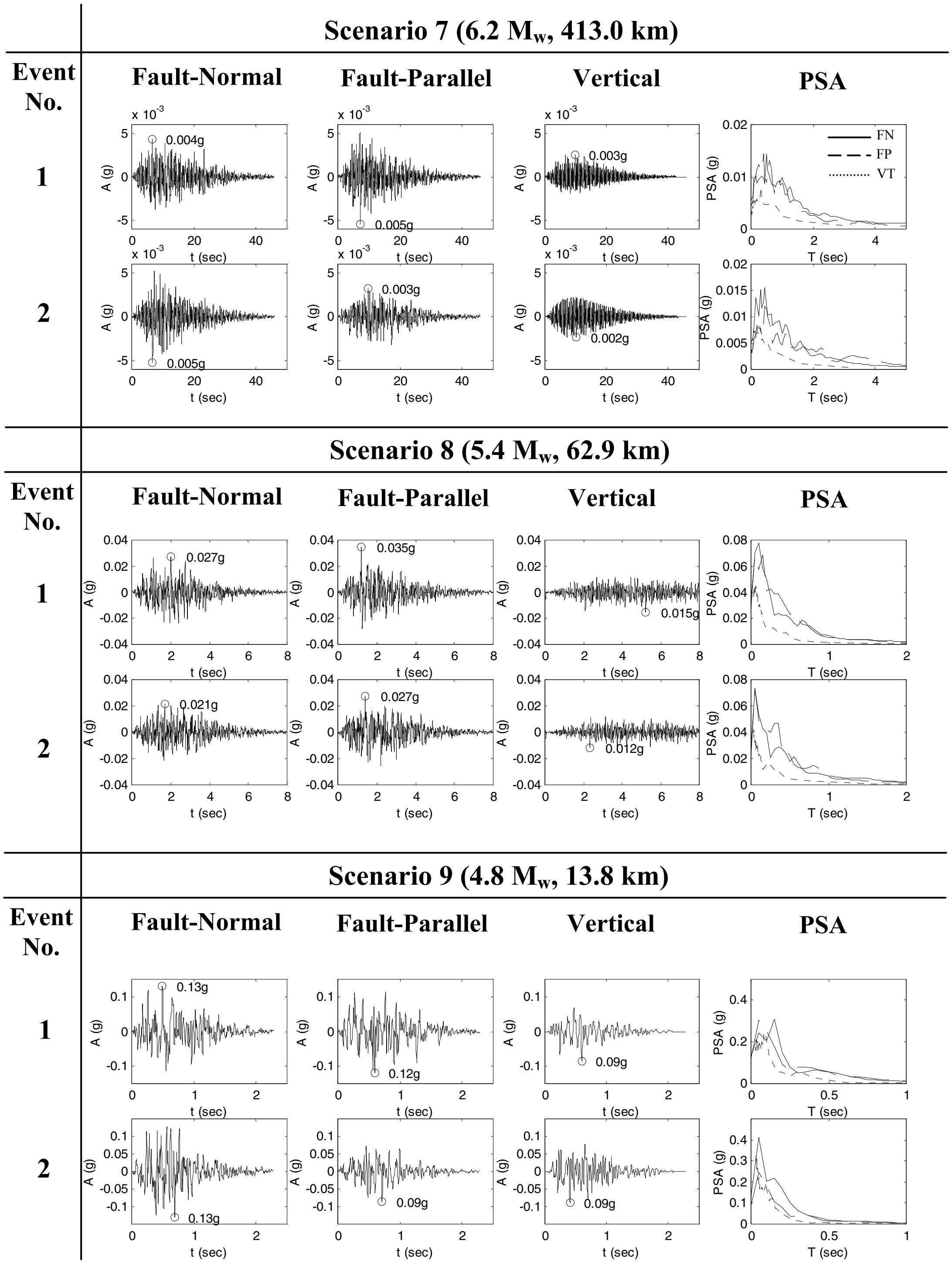


Figure C-4 New York : 20% Probability of Exceedance in 50 Years Long Ensemble (Cont'd)

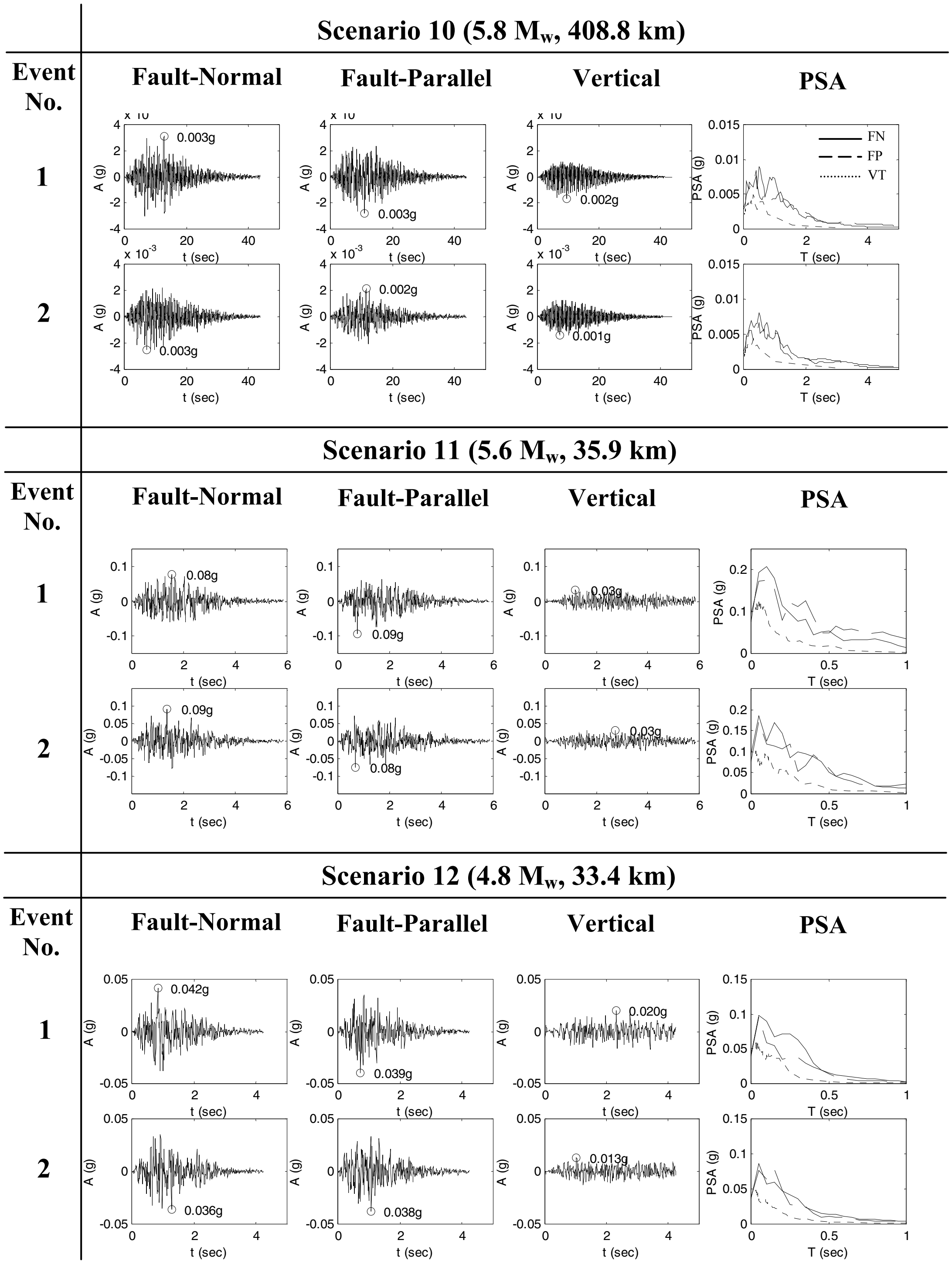


Figure C-4 New York : 20% Probability of Exceedance in 50 Years Long Ensemble (Cont'd)

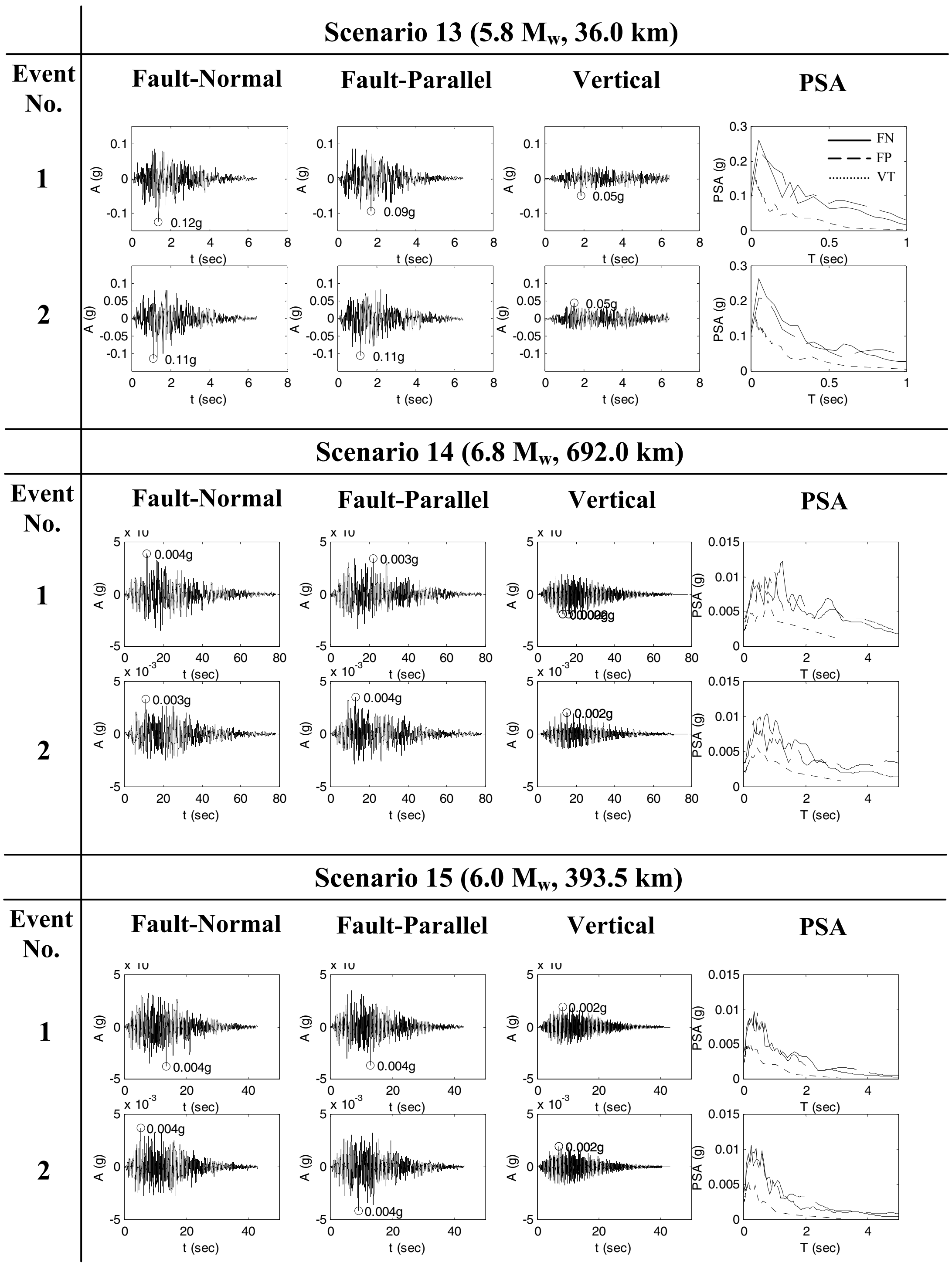


Figure C-4 New York : 20% Probability of Exceedance in 50 Years Long Ensemble (Cont'd)

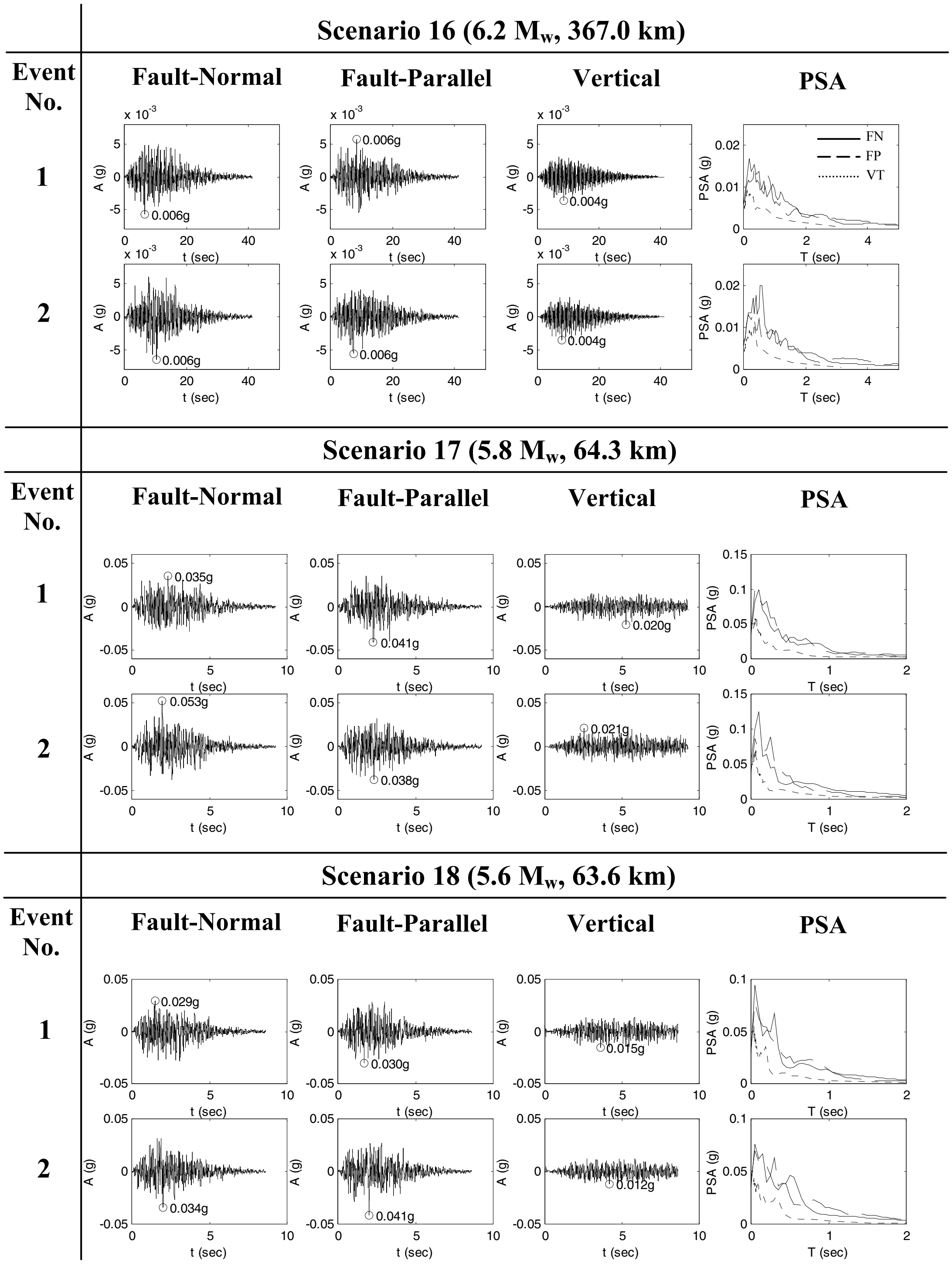


Figure C-4 New York : 20% Probability of Exceedance in 50 Years Long Ensemble (Cont'd)

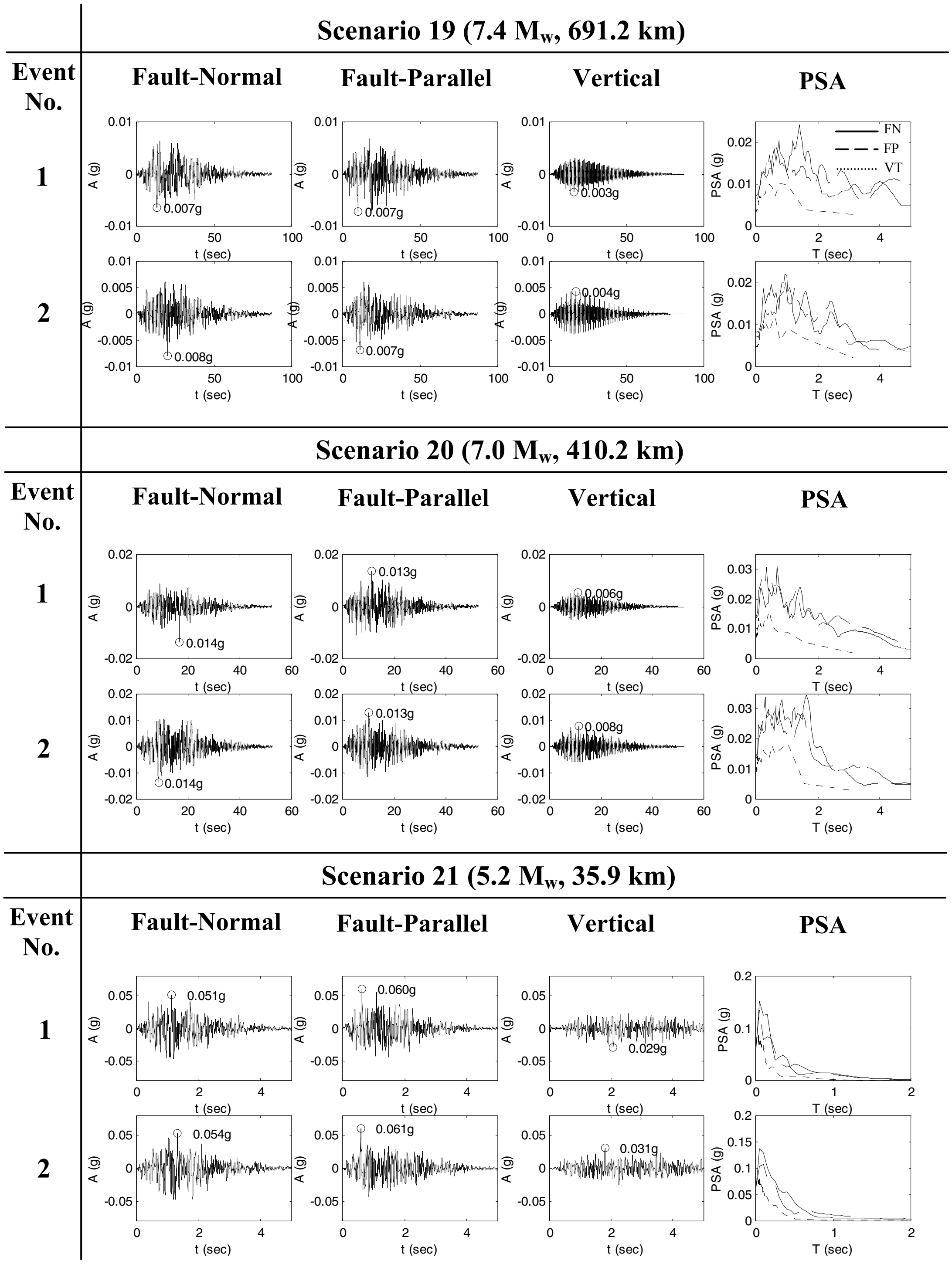


Figure C-4 New York : 20% Probability of Exceedance in 50 Years Long Ensemble (Cont'd)

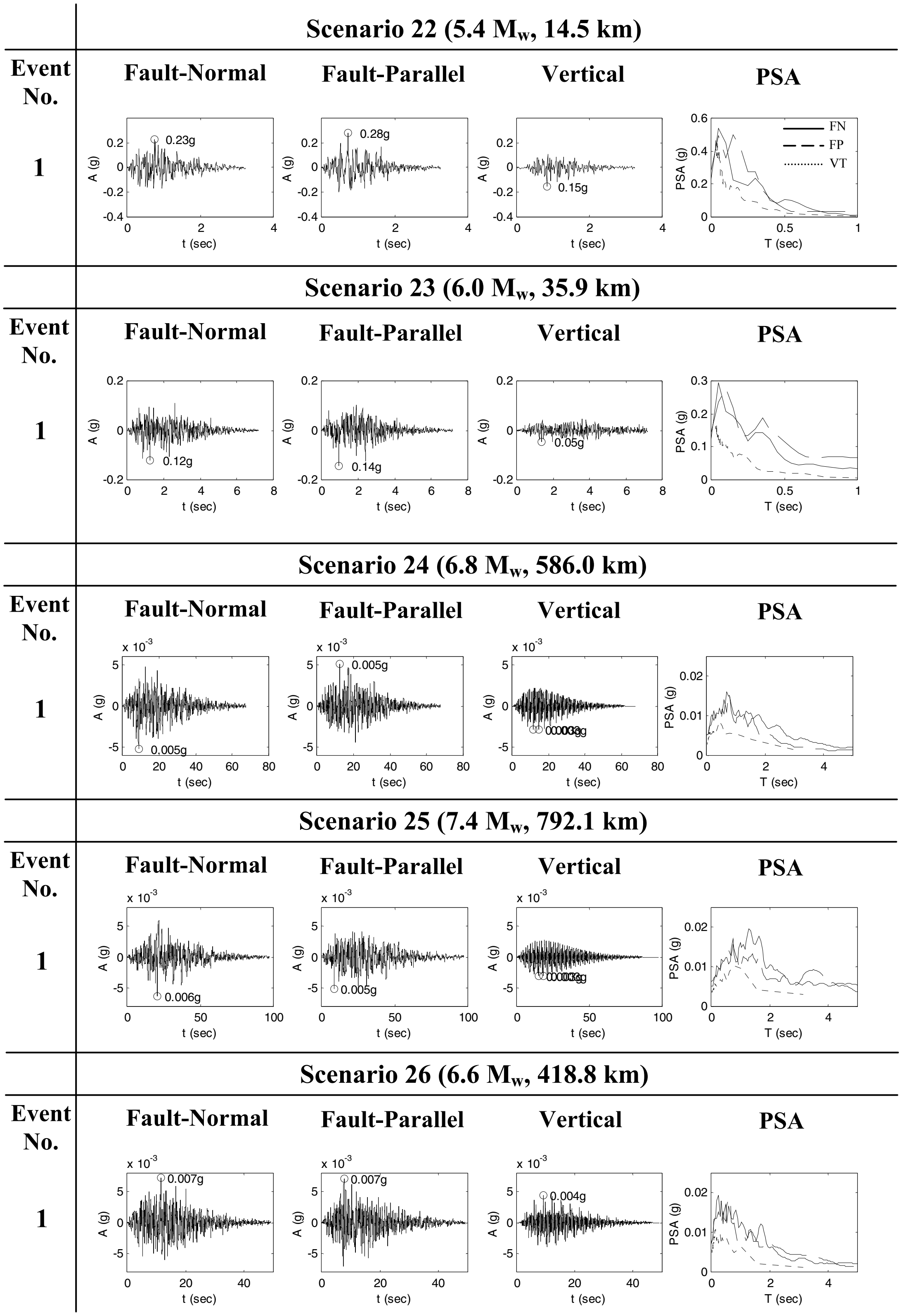


Figure C-4 New York : 20% Probability of Exceedance in 50 Years Long Ensemble (Cont'd)

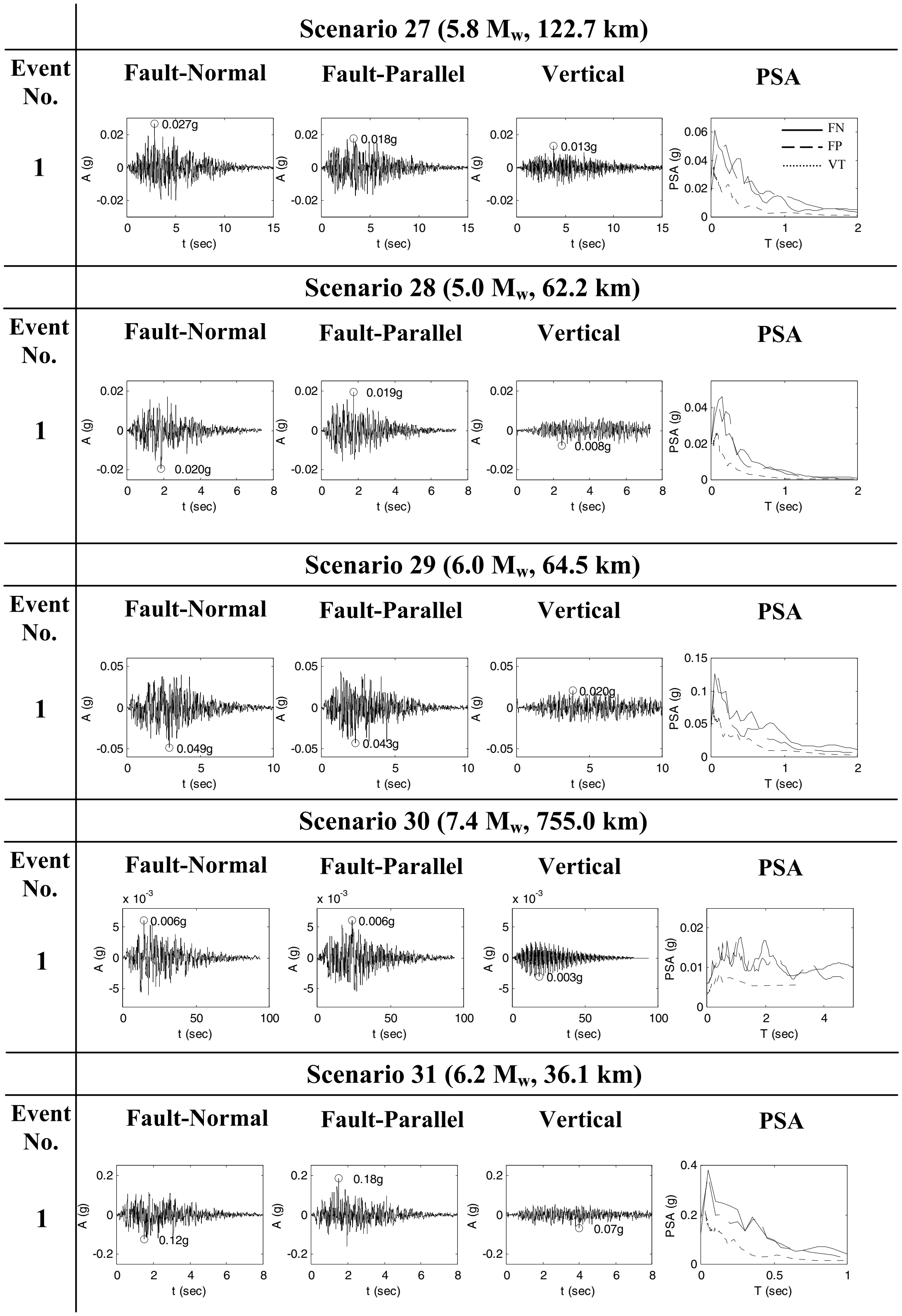
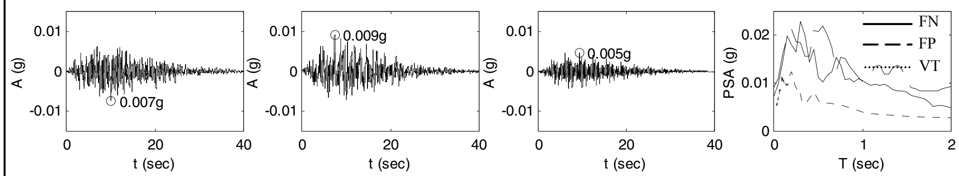


Figure C-4 New York : 20% Probability of Exceedance in 50 Years Long Ensemble (Cont'd)

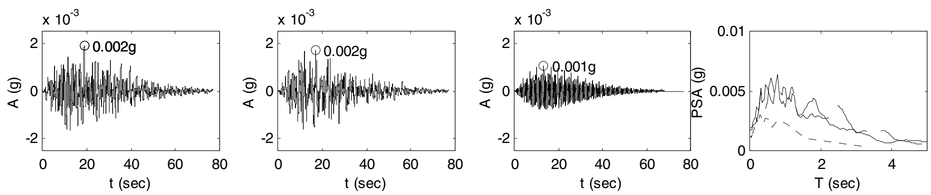
Scenario 32 (6.4 M_w, 342.6 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				



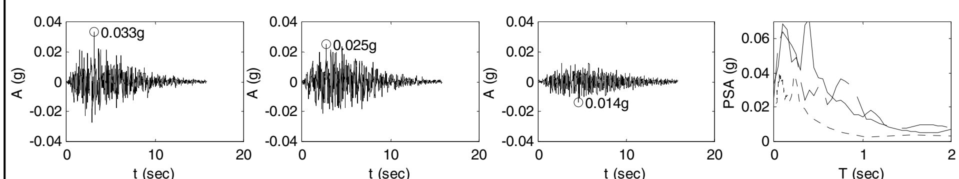
Scenario 33 (6.4 M_w, 711.7 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				



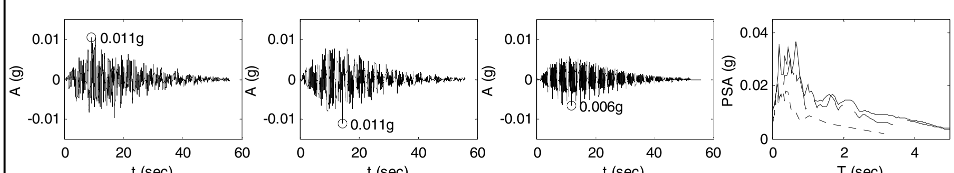
Scenario 34 (6.0 M_w, 122.1 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				



Scenario 35 (7.0 M_w, 444.3 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				



Scenario 36 (7.3 M_w, 906.7 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				

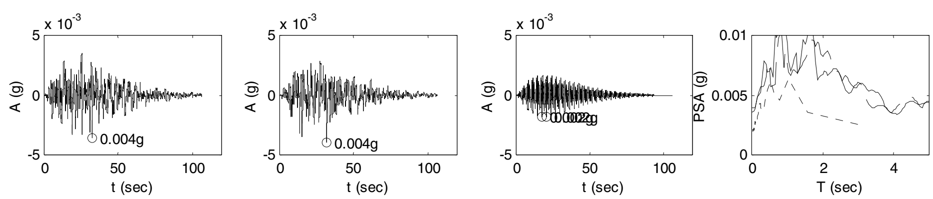


Figure C-4 New York : 20% Probability of Exceedance in 50 Years Long Ensemble (Cont'd)

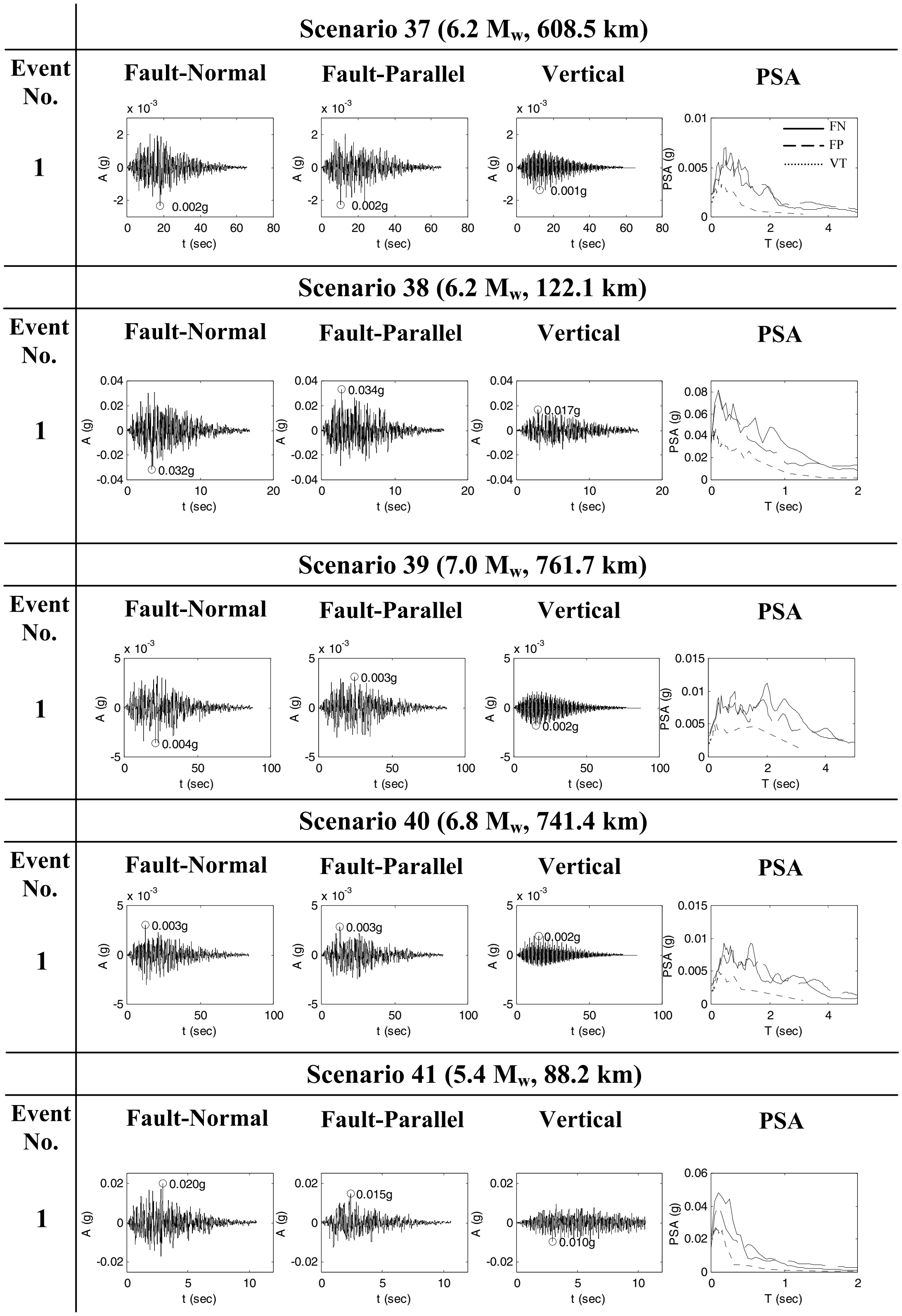
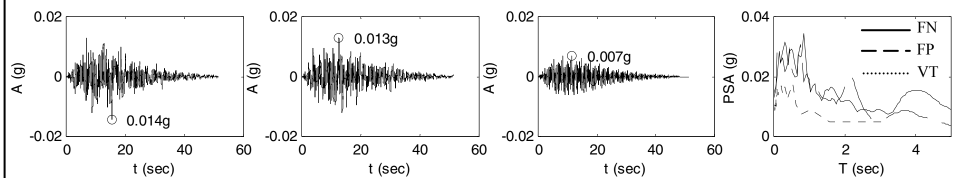


Figure C-4 New York : 20% Probability of Exceedance in 50 Years Long Ensemble (Cont'd)

Scenario 42 (7.0 M_w, 398.5 km)

Event No. | **Fault-Normal** | **Fault-Parallel** | **Vertical** | **PSA**

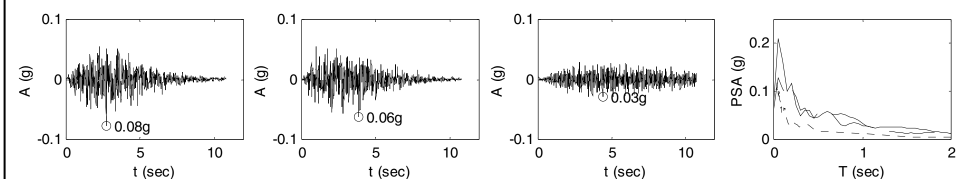
1



Scenario 43 (6.2 M_w, 62.6 km)

Event No. | **Fault-Normal** | **Fault-Parallel** | **Vertical** | **PSA**

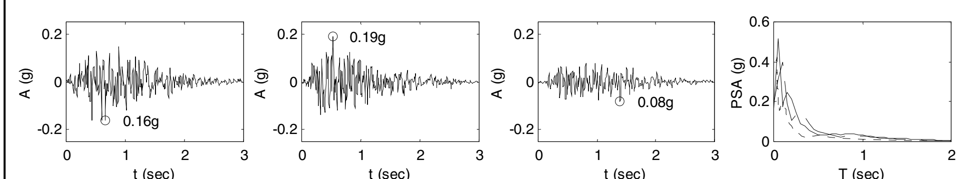
1



Scenario 44 (5.2 M_w, 15.5 km)

Event No. | **Fault-Normal** | **Fault-Parallel** | **Vertical** | **PSA**

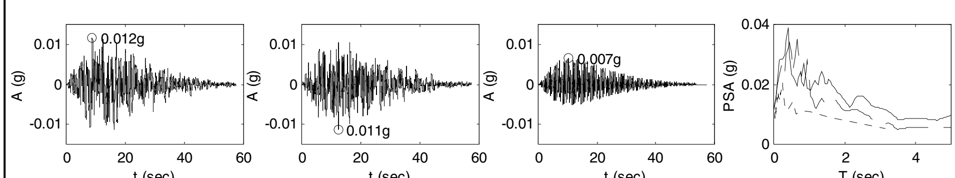
1



Scenario 45 (7.2 M_w, 431.7 km)

Event No. | **Fault-Normal** | **Fault-Parallel** | **Vertical** | **PSA**

1



Scenario 46 (5.4 M_w, 120.2 km)

Event No. | **Fault-Normal** | **Fault-Parallel** | **Vertical** | **PSA**

1

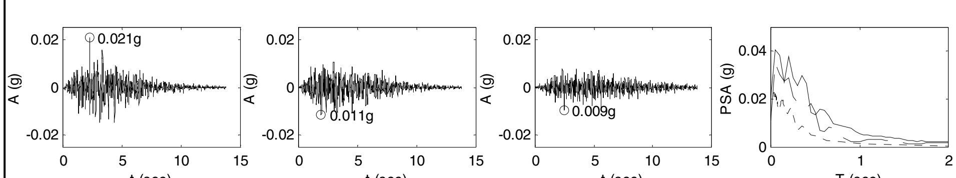
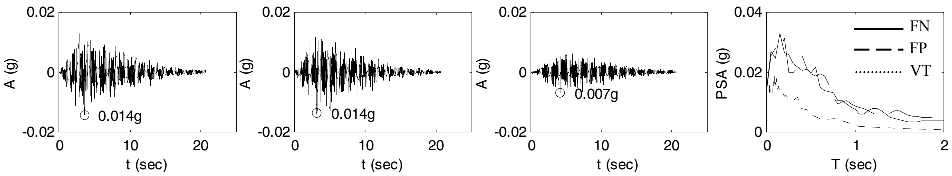


Figure C-4 New York : 20% Probability of Exceedance in 50 Years Long Ensemble (Cont'd)

Scenario 47 (5.8 M_w, 177.5 km)

Event No. | **Fault-Normal** | **Fault-Parallel** | **Vertical** | **PSA**

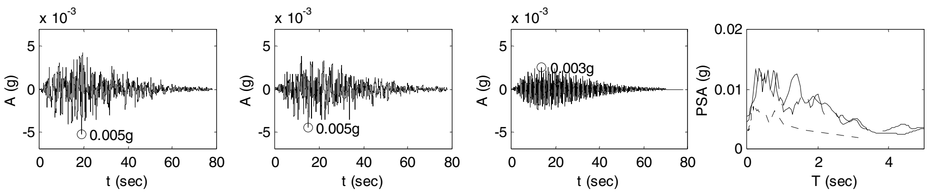
1



Scenario 48 (7.0 M_w, 664.6 km)

Event No. | **Fault-Normal** | **Fault-Parallel** | **Vertical** | **PSA**

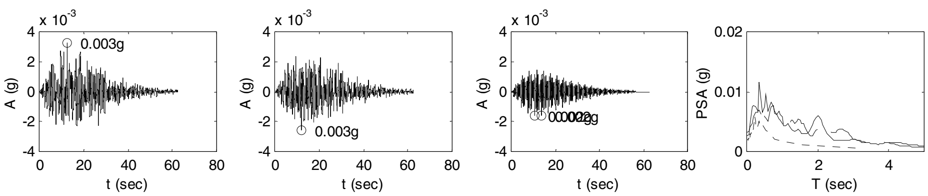
1



Scenario 49 (6.4 M_w, 569.6 km)

Event No. | **Fault-Normal** | **Fault-Parallel** | **Vertical** | **PSA**

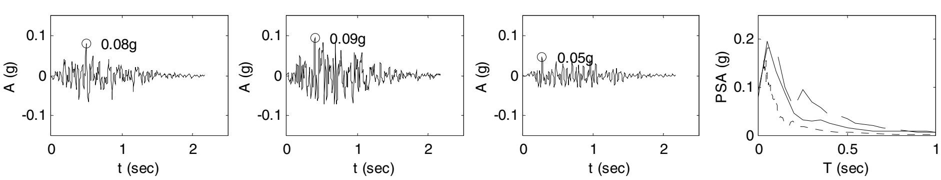
1



Scenario 50 (4.6 M_w, 14.6 km)

Event No. | **Fault-Normal** | **Fault-Parallel** | **Vertical** | **PSA**

1



Scenario 51 (6.8 M_w, 353.6 km)

Event No. | **Fault-Normal** | **Fault-Parallel** | **Vertical** | **PSA**

1

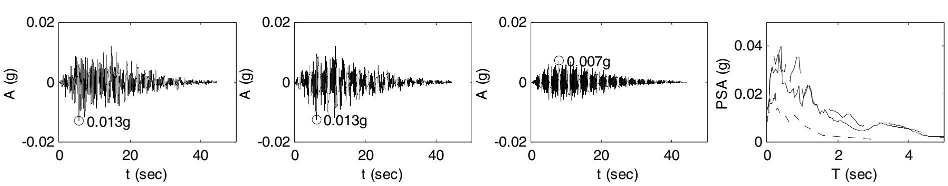


Figure C-4 New York : 20% Probability of Exceedance in 50 Years Long Ensemble (Cont'd)

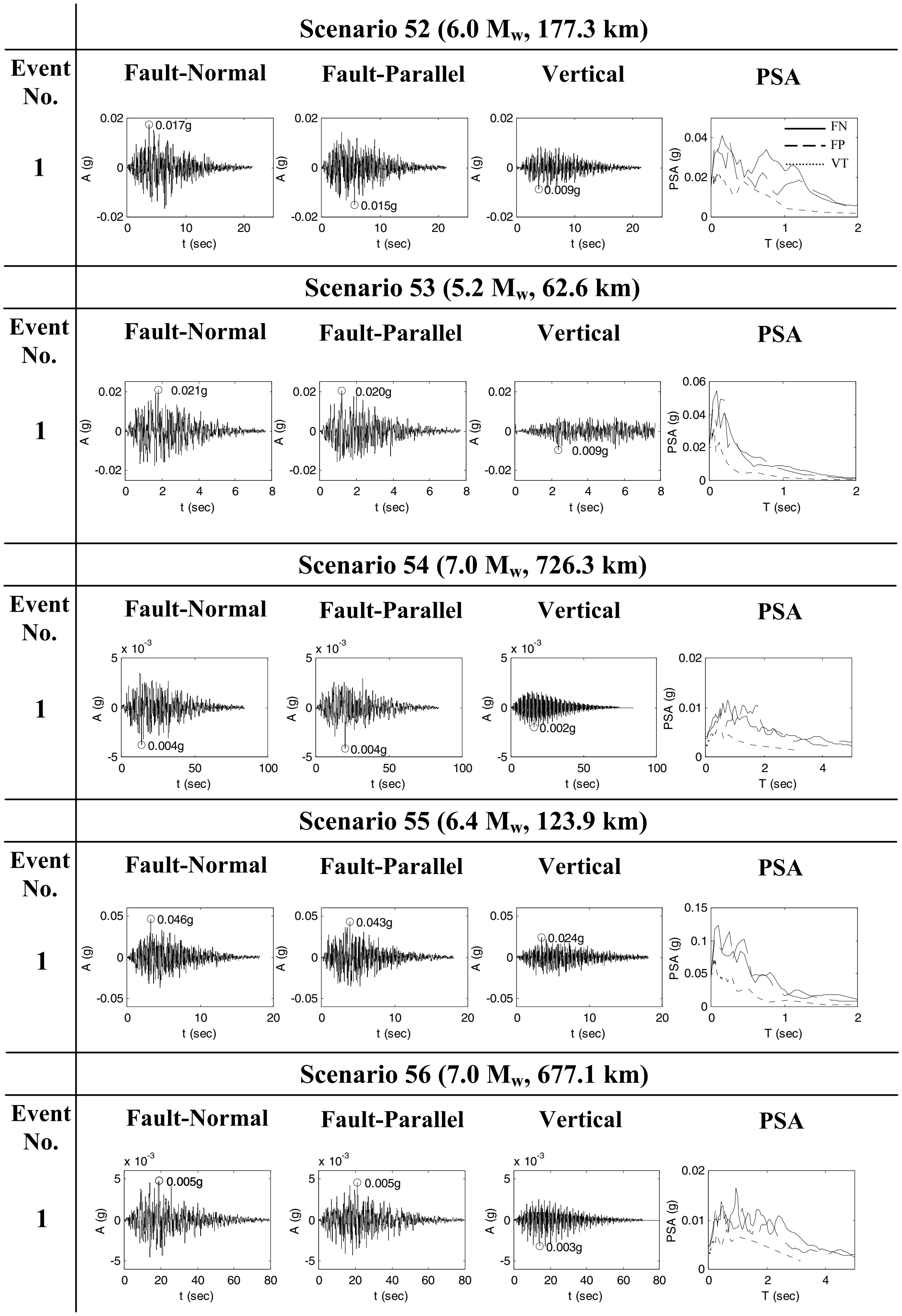
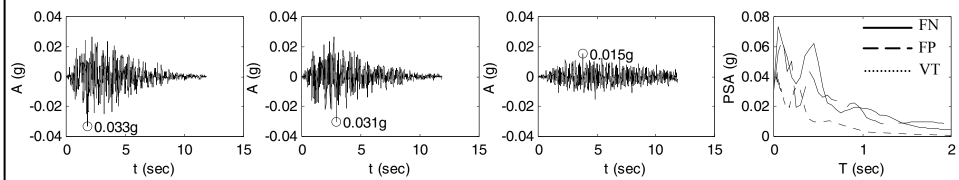


Figure C-4 New York : 20% Probability of Exceedance in 50 Years Long Ensemble (Cont'd)

Scenario 57 (5.8 M_w, 90.0 km)

Event No. | **Fault-Normal** | **Fault-Parallel** | **Vertical** | **PSA**

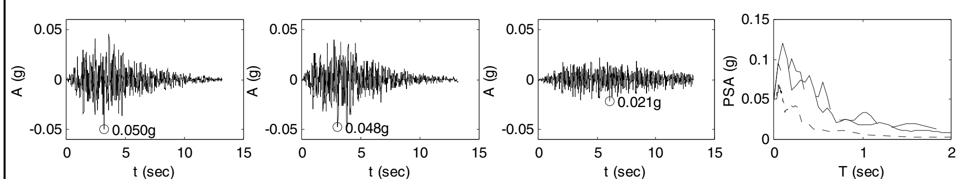
1



Scenario 58 (6.2 M_w, 86.6 km)

Event No. | **Fault-Normal** | **Fault-Parallel** | **Vertical** | **PSA**

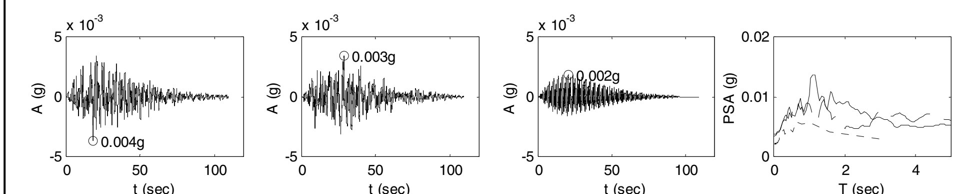
1



Scenario 59 (7.3 M_w, 935.3 km)

Event No. | **Fault-Normal** | **Fault-Parallel** | **Vertical** | **PSA**

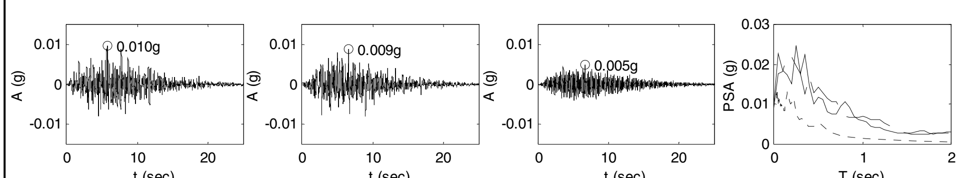
1



Scenario 60 (5.8 M_w, 222.6 km)

Event No. | **Fault-Normal** | **Fault-Parallel** | **Vertical** | **PSA**

1



Scenario 61 (6.0 M_w, 544.7 km)

Event No. | **Fault-Normal** | **Fault-Parallel** | **Vertical** | **PSA**

1

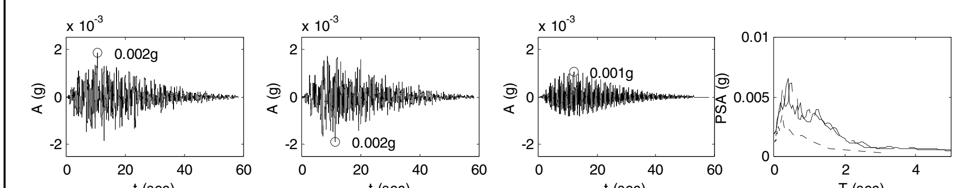
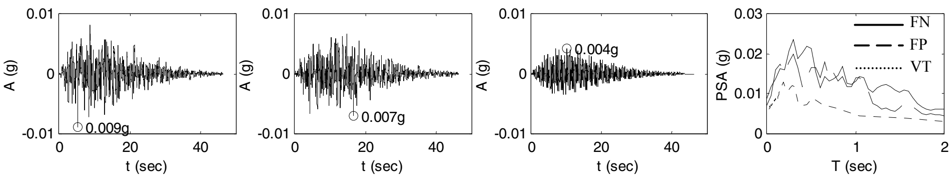


Figure C-4 New York : 20% Probability of Exceedance in 50 Years Long Ensemble (Cont'd)

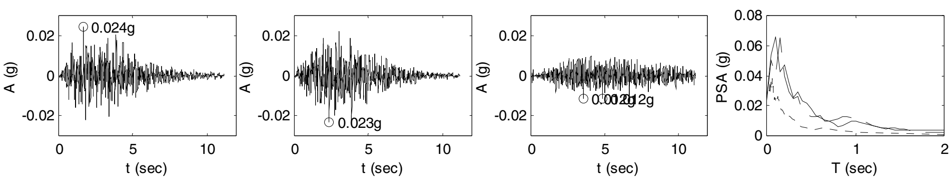
Scenario 62 (6.6 M_w, 389.5 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				



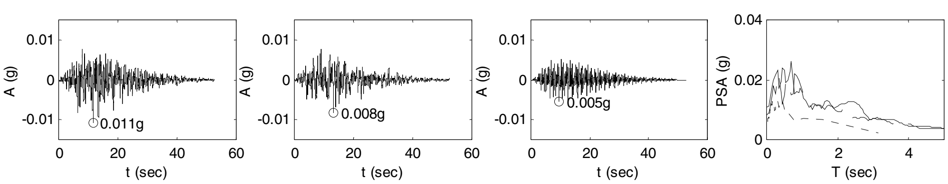
Scenario 63 (5.6 M_w, 89.2 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				



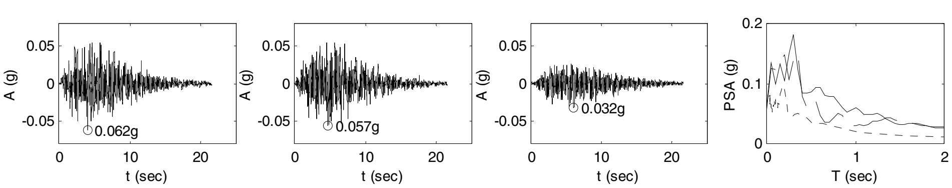
Scenario 64 (6.8 M_w, 436.1 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				



Scenario 65 (6.8 M_w, 124.8 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				



Scenario 66 (6.2 M_w, 699.0 km)

Event No.	Fault-Normal	Fault-Parallel	Vertical	PSA
1				

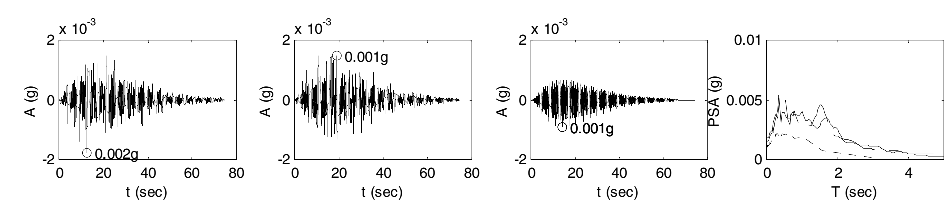
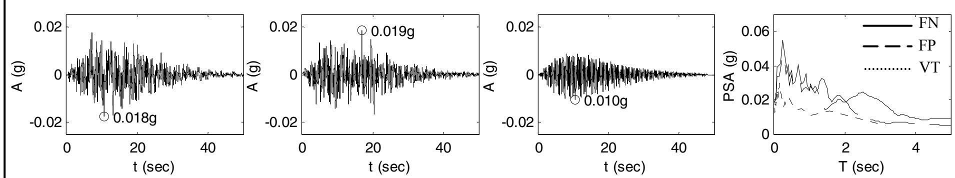


Figure C-4 New York : 20% Probability of Exceedance in 50 Years Long Ensemble (Cont'd)

Scenario 67 (7.2 M_w, 361.0 km)

Event No. | **Fault-Normal** | **Fault-Parallel** | **Vertical** | **PSA**

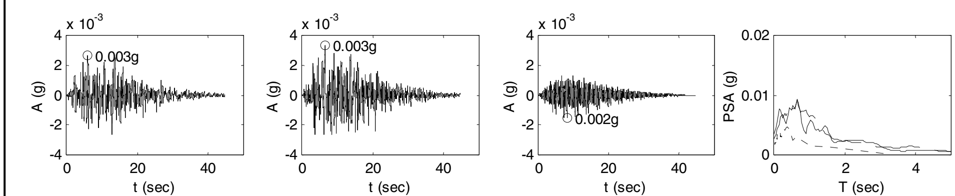
1



Scenario 68 (6.0 M_w, 410.7 km)

Event No. | **Fault-Normal** | **Fault-Parallel** | **Vertical** | **PSA**

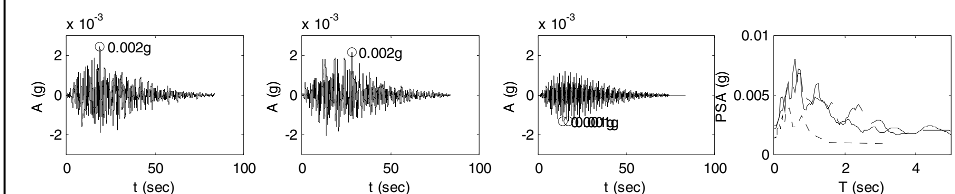
1



Scenario 69 (6.6 M_w, 762.3 km)

Event No. | **Fault-Normal** | **Fault-Parallel** | **Vertical** | **PSA**

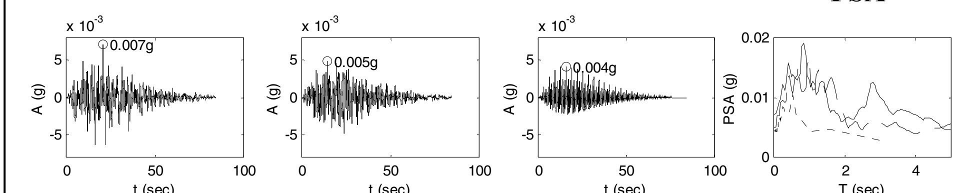
1



Scenario 70 (7.2 M_w, 700.0 km)

Event No. | **Fault-Normal** | **Fault-Parallel** | **Vertical** | **PSA**

1



Scenario 71 (6.6 M_w, 539.8 km)

Event No. | **Fault-Normal** | **Fault-Parallel** | **Vertical** | **PSA**

1

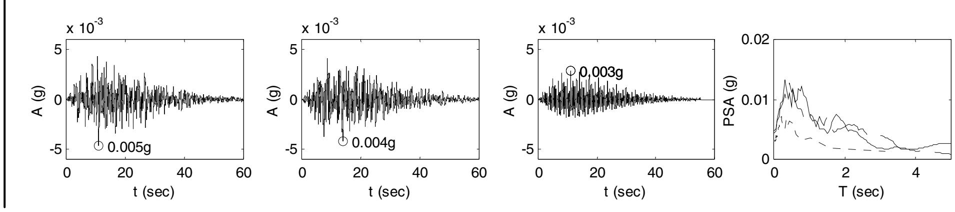
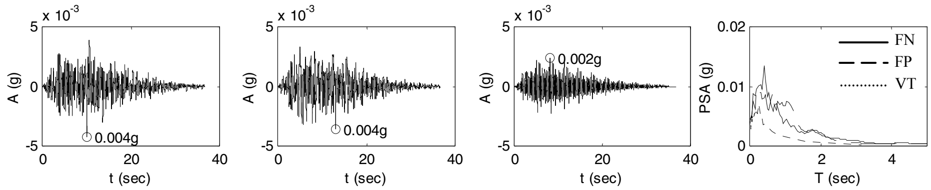


Figure C-4 New York : 20% Probability of Exceedance in 50 Years Long Ensemble (Cont'd)

Event No.	Scenario 72 (5.8 M_w, 337.7 km)			
	Fault-Normal	**Fault-Parallel**	**Vertical**	**PSA**
1				

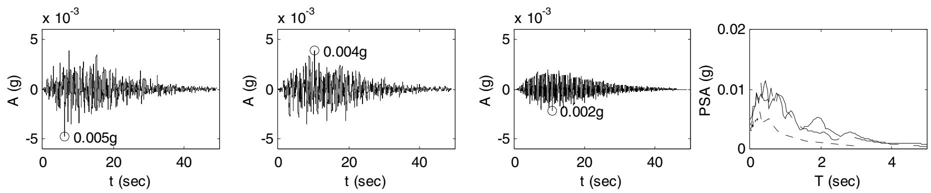
Event No.	Scenario 73 (6.2 M_w, 445.1 km)			
	Fault-Normal	**Fault-Parallel**	**Vertical**	**PSA**
1				

Figure C-4 New York : 20% Probability of Exceedance in 50 Years Long Ensemble (Cont'd)

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