Nonlinear Responses of High-rise Buildings in Seattle for Simulated Ground Motions from Giant Cascadia Subduction Earthquakes (M_W 9.2)

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1. Introduction

With the exception of the 2003 Tokachi-oki earthquake, strong ground recordings from large subduction earthquakes ($M_W > 8.0$) are meager. Furthermore there are no strong motion recordings of giant earthquakes. However, there is a growing set of high-quality broadband teleseismic recordings of large and giant earthquakes. In our study, we use recordings from the 2003 Tokachi-oki (M_W 8.3) earthquake as empirical Green's functions to simulate the rock and soil ground motions from a scenario M_W 9.2 subduction earthquake on Cascadia subduction zone in the frequency band of interest to flexible and large-scale buildings (0.075 to 1 Hz). The effect of amplification by the Seattle basin is considered by using a basin response Green's function which is derived from deconvolving the teleseismic waves recorded at rock sites from soil sites at the SHIP02 experiment[1]. These strong ground motions are used to excite simulations of the fully nonlinear seismic responses of 20-story steel moment-frame buildings designed according to both the U.S. 1994 UBC and also the Japanese building code published in 1987. We consider several realizations of the hypothetical subduction earthquake; the down-dip limit of rupture is of particular importance to the simulated ground motions in Seattle. If slip is assumed to be limited to offshore regions, then the building simulations indicate that the building responses are mostly in the linear range. However, our simulation shows that buildings with brittle welds would collapse for rupture models where rupture extends beneath the Olympic Mountains. The ground motions all have very long durations (more than 4 minutes), and our building simulations should be considered as a minimum estimate since we have used a very simple model of degradation of the structure.

2. Empirical Green's Functions Method[2]

Assumption: Ground motions from large EQ are a linear combination of smaller ones.

$$U(t)=\sum_{i=1}^{l}\sum_{j=1}^{m}U_{ij}(t)=\sum_{i=1}^{l}\sum_{j=1}^{m}\int_{(i-1)\Delta L}^{i\Delta L}\int_{(j-1)\Delta W}^{j\Delta W}\dot{D}(x,y,t)*G(x,y,t)\,dydx$$

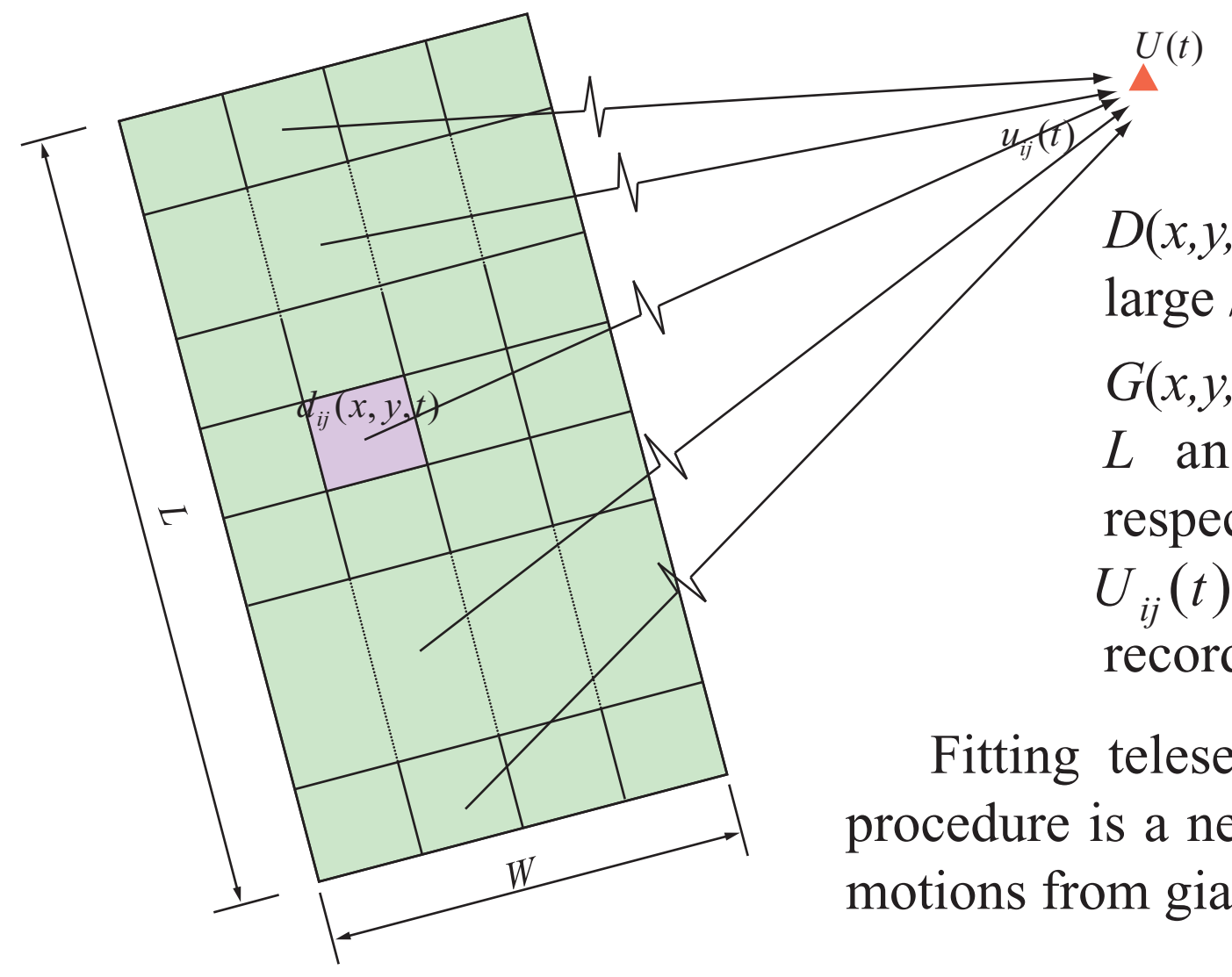
$$=\sum_{i=1}^{l}\sum_{j=1}^{m}F_{ij}(t)*u_{ij}(t)=\sum_{i=1}^{l}\sum_{j=1}^{m}\sum_{k=1}^{n}u_{ij}\left[t-T_{ij}-(k-\chi_k)\frac{t_d}{n}\right]$$

Assume:

$$D(x,y,t)=F_{ij}(t)*d_{ij}(x,y,t)$$

$$F_{ij}(t)=\sum_{k=1}^{n}\delta(t-T_{ij}-\tau_k)$$

$$\tau_k=(k-\chi_k)\frac{t_d}{n}$$



near field or far field station

D(*x*,*y*,*t*) / *d*(*x*,*y*,*t*): distribution of dislocation time histories for large /small earthquakes.

G(*x*,*y*,*t*): double-couple impulse response of the medium.

L and *W* are length and width of the planar fault, respectively.

$U_{ij}(t)$ are either teleseismic data or strong ground motion recordings.

Fitting teleseismic P-wave data from giant earthquakes with this procedure is a necessary condition for this procedure to simulate strong motions from giant earthquakes.

3. Choosing Earthquakes

The hypothetical giant Cascadia subduction earthquake is assumed to have a similar source model to the 2004 Sumatra-Andaman earthquake (M_W9.2) because these two areas have similar tectonic settings.

Choose the 2003 Tokachi-oki M_W8.3 earthquake as EGF

- Have an excellent set of high-quality teleseismic and strong ground recordings.
- Amplitude is closest to the simulated Cascadia event thus requiring the smallest extrapolation from great to giant events
- The body wave spectrum, depth and dip have similar characteristics (especially in the frequency band 0.05 - 1 Hz) with Sumatra event.

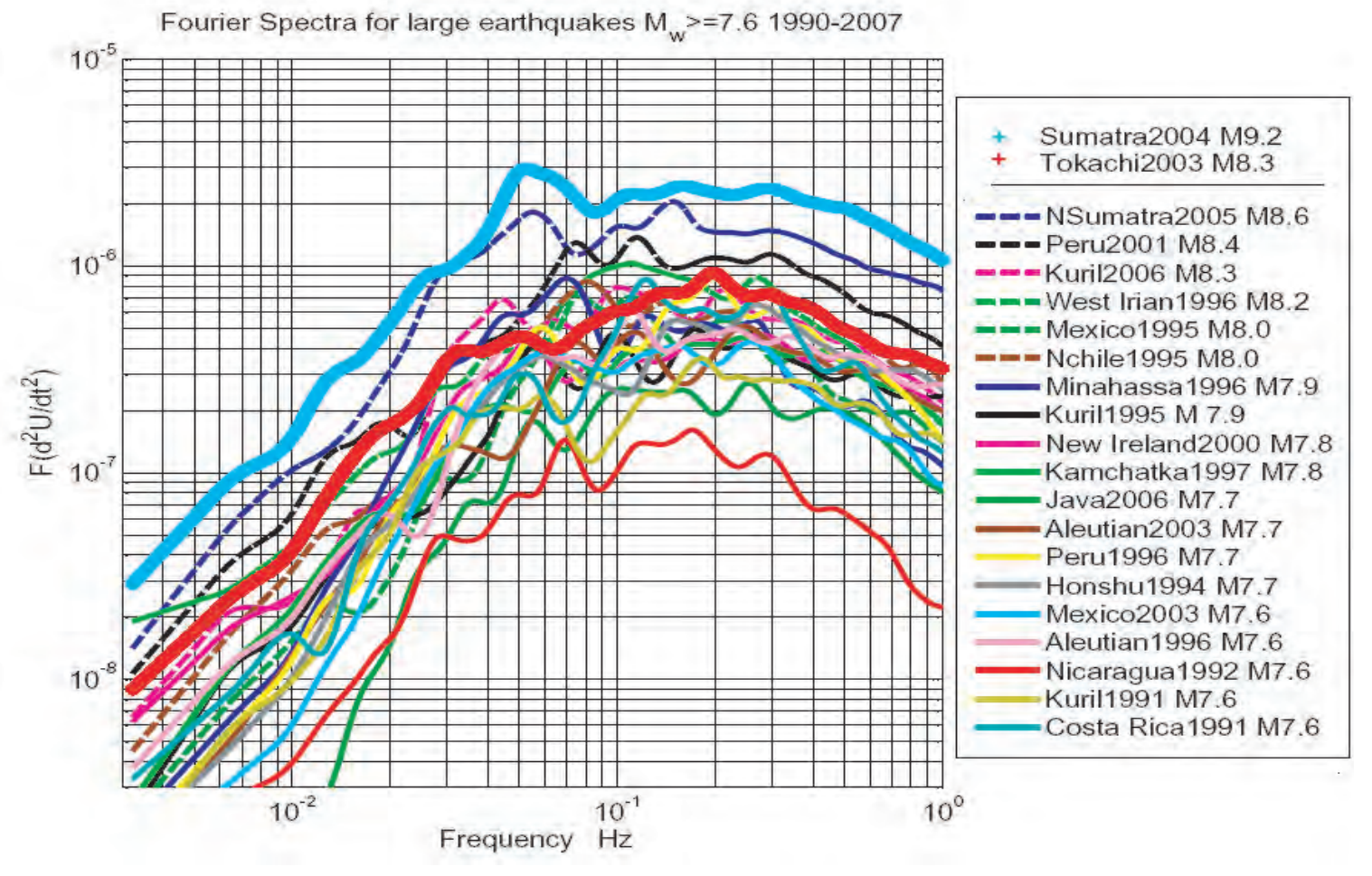


Figure. Smoothed P-wave Fourier spectra of the teleseismic acceleration averaged at a distance of 60° for shallow subduction earthquakes larger than M_W 7.6 during 1990 to present.

Acknowledgement:

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Teleseismic data is from IRIS and strong ground motion recordings are from K-Net and KiK-Net. Building responses are calculated at SCEC High Performance Computing Center.
SHIP02 data is from Prof. Thomas Pratt at University of Washington.
Steve Hartzell provides key part of the empirical Green's function code and John Hall provides Frame-2D program.

4. Tectonic Settings

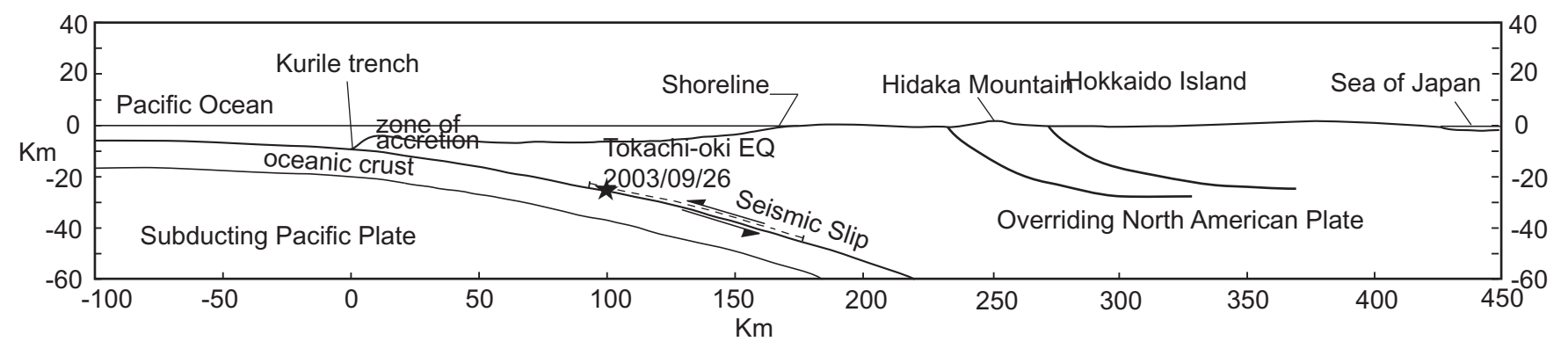
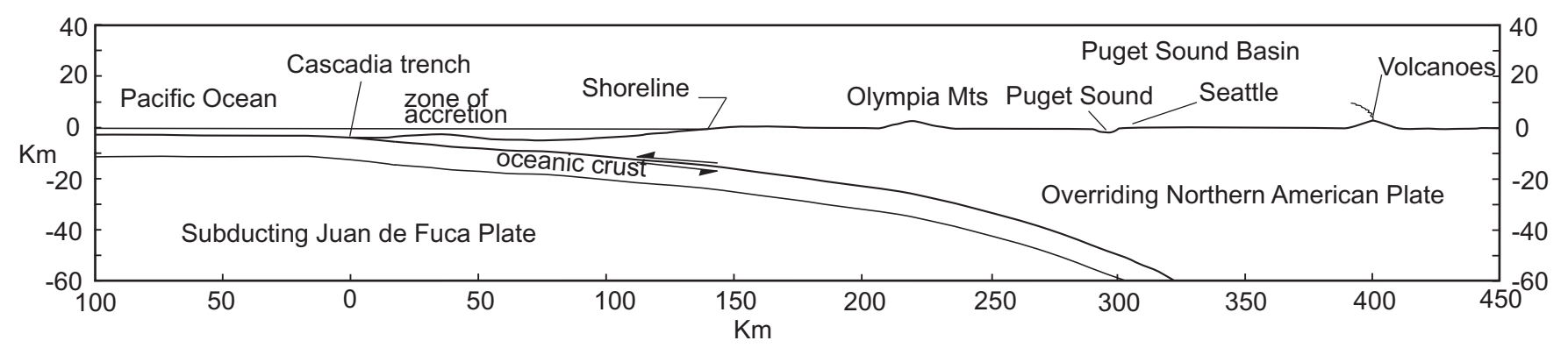


Figure: Cross section of the approximate geometry of the rupture surface. No depth exaggeration



Tokachi-oki 2003 Earthquake Model[3,4] as empirical Green's function

M_W	8.0 ~ 8.3
Scalar Moment:	(1.0 ~ 2.2)X10^{21} N·m
Rupture Fault:	120X80 km^2
Fault Depth:	25 - 50 km
Maximum Slip:	6 m
Rupture Velocity:	2.7 km/s

Cascadia Subduction Earthquake Model

use the 2004 Sumatra- Andaman Earthquake Model[5,6]

M_W	9.2
Scalar Moment:	(4.0 ~ 6.6) X10^{22} N·m
Rupture fault:	1300X(200±40) km^2
Fault Depth:	5 - 60 km
Rupture velocity:	2 ~ 3km/s

5. Site Amplification

Goal: Find Green's functions representing how waves are amplified by the Seattle basin. That is finding *G(t)* which satisfies *Rock(t) * G(t) = Soil(t)*
where *Rock(t)* are motions recorded at bedrock sites, *Soil(t)* are motions recorded at Seattle basin sites.

Data: Teleseismic s-waves collected at SHIP02 experiment.

Method: Use damped least square method to solve the deconvolution problem in time domain.

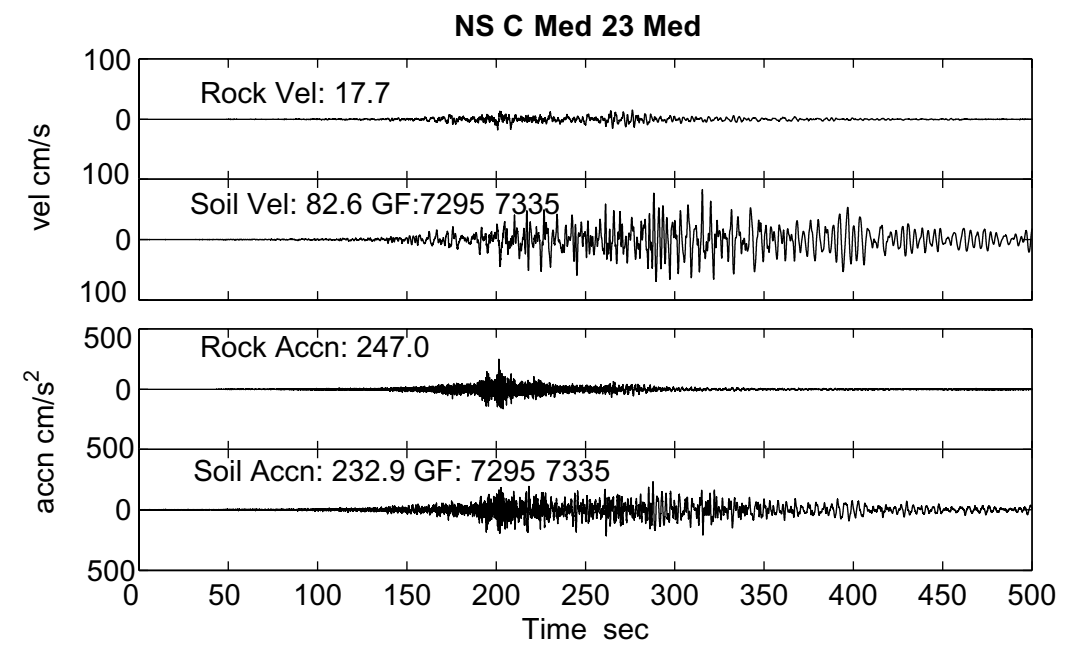
$$s_j=(r*g)_j=\sum_{k=1}^{N}r_k g_{j-k}$$

$$\begin{bmatrix} r_1 & r_n & r_{n-1} & \cdots & \cdots & r_2\\ r_2 & r_1 & r_n & \cdots & \cdots & r_3\\ r_3 & r_2 & r_1 & \cdots & \cdots & r_4\\ \vdots & \vdots & \vdots & \cdots & \cdots & \vdots\\ \vdots & \vdots & \vdots & \cdots & \cdots & \vdots\\ r_n & r_{n-1} & r_{n-2} & \cdots & \cdots & r_1 \end{bmatrix}\begin{bmatrix} g_1\\ g_2\\ g_3\\ \vdots\\ \vdots\\ g_n\end{bmatrix}\cong\begin{bmatrix} s_1\\ s_2\\ s_3\\ \vdots\\ \vdots\\ s_n\end{bmatrix}$$

denote as $Ax\cong b$

Singular value decomposition is used to stabilize the inversion of ill-conditioned matrices

$$\begin{bmatrix}A\\ \lambda F\end{bmatrix}x\cong\begin{bmatrix}b\\ \lambda d\end{bmatrix}$$ where, $A=USV^T$ $F=VHV^T$ For details, see ref 8.



Left figure: A pair of rock motions and soil motions amplified by Green's function.

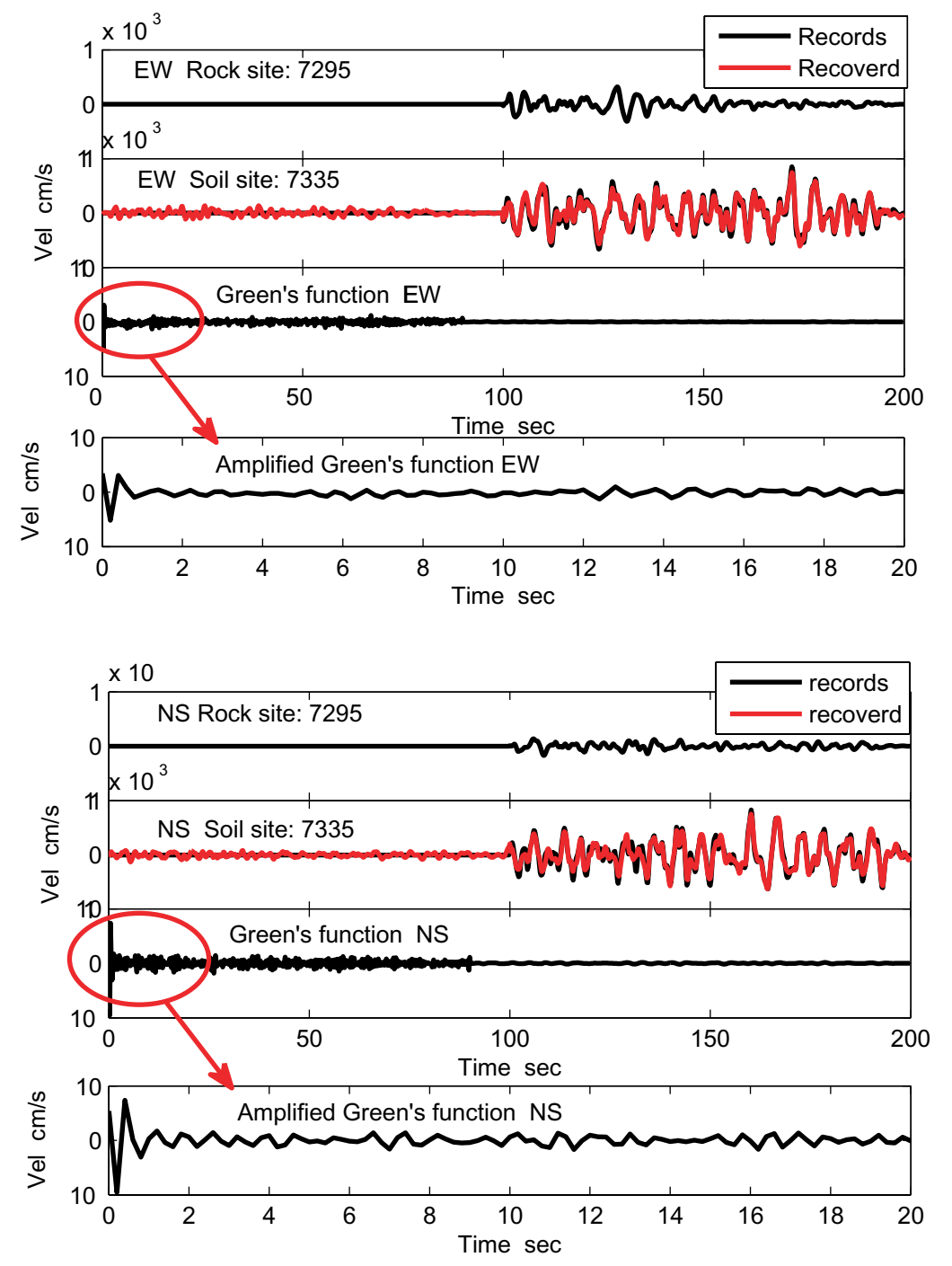


Figure: Resulting Green's functions time history

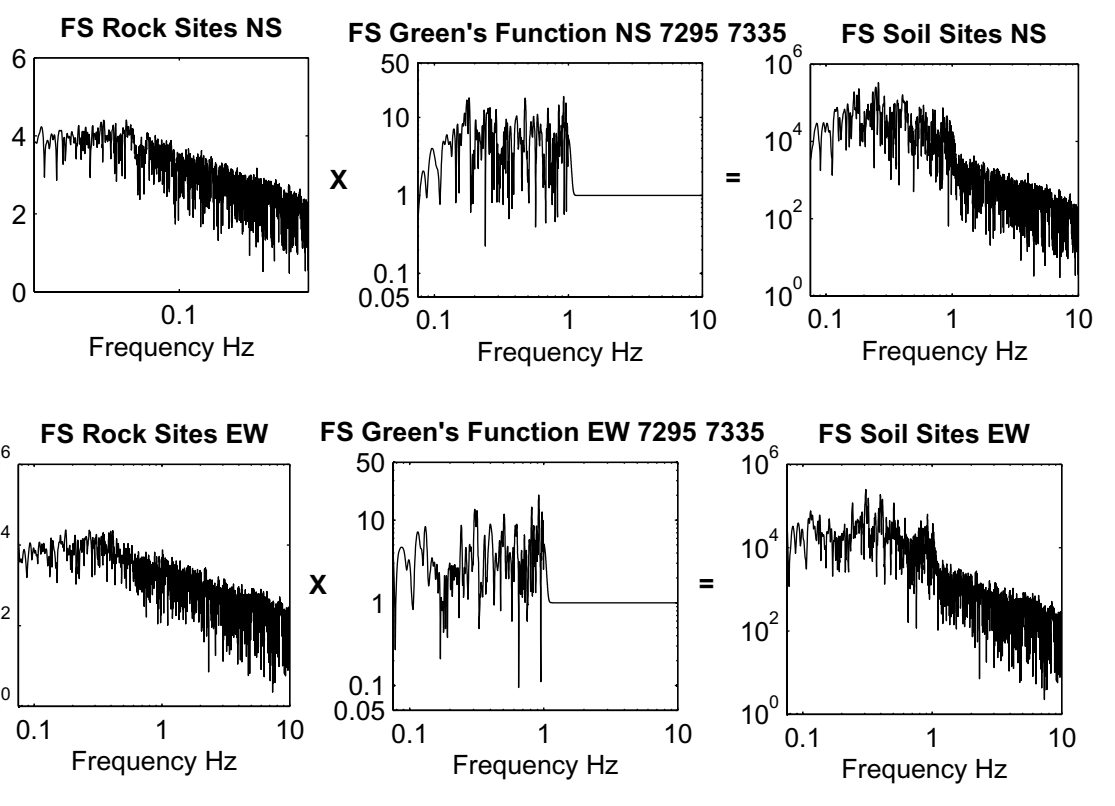
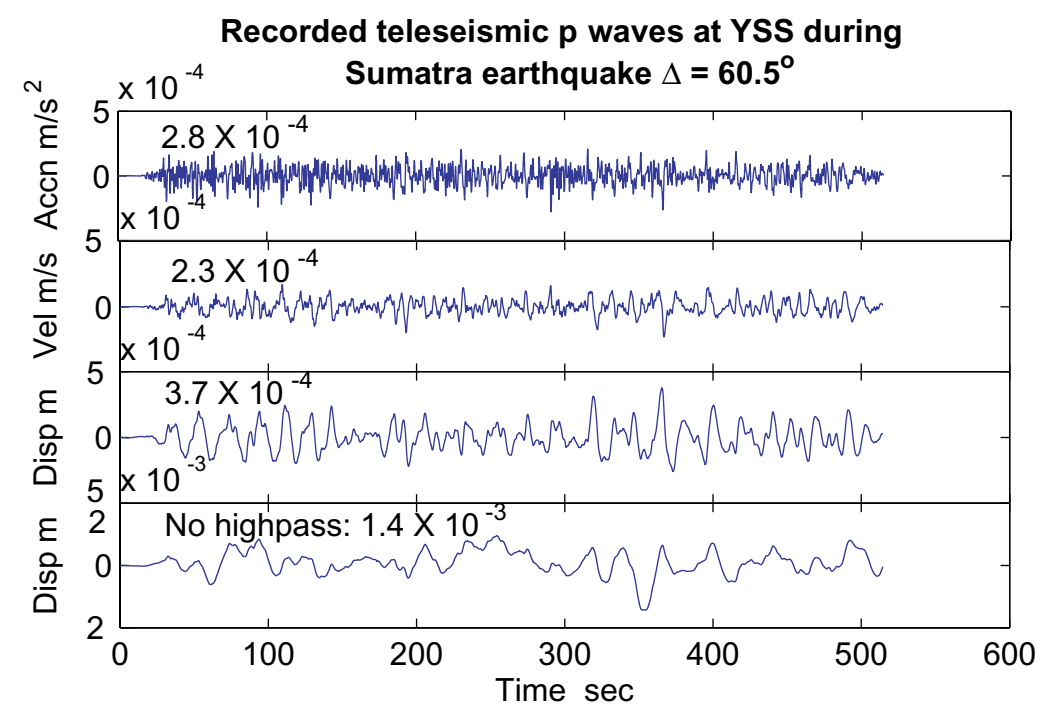


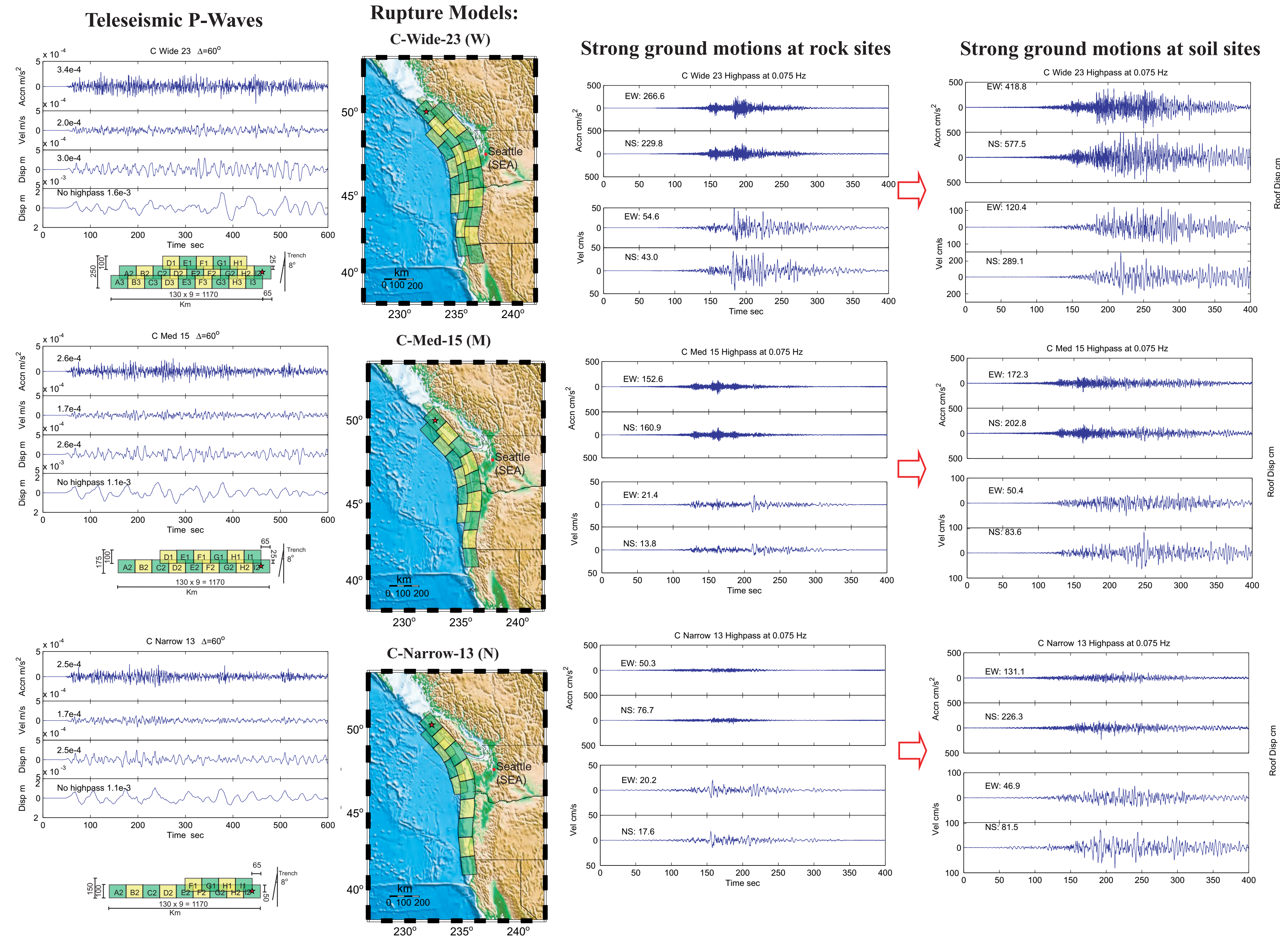
Figure: Convolve Green's function with simulated ground motions at rock sites to get motions at soil sites.

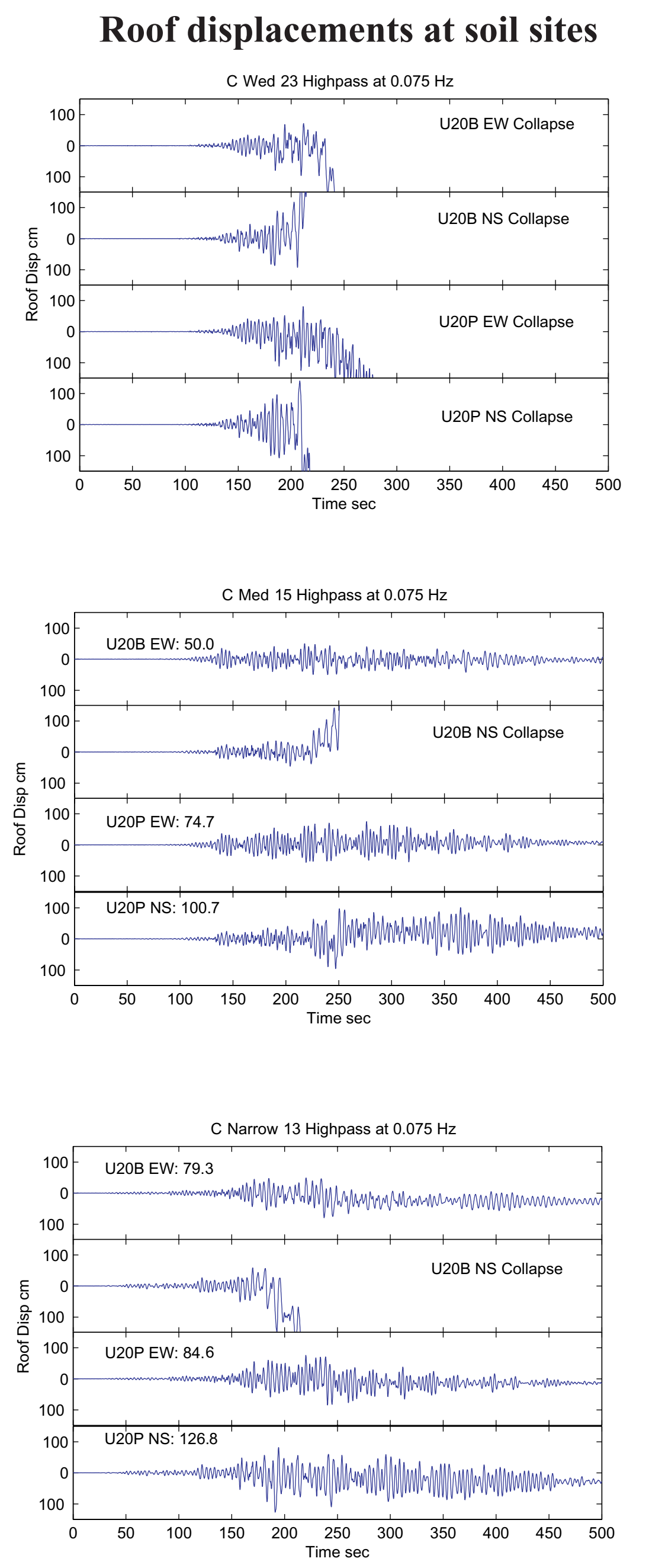
6. Simulated Results for Different Rupture Models



The hypothetical giant Cascadia subduction earthquake is assumed to have a similar source model to the 2004 Sumatra-Andaman earthquake (M_W9.2) because these two areas have similar tectonic settings. The teleseismic p-waves recorded for the Sumatra event are used to constrain the number of subfaults summed in the empirical Green's function method.

3 rupture models (with different fault widths) were used to simulate the strong ground motions in the Seattle area. Site Amplification was applied to estimate the motions in the Seattle basin. The roof displacements of 20-story steel moment-frame buildings designed according to UBC94 with brittle welds (U20B) and perfect welds (U20P) were shown for each model. From the figures in this section we see that the down-dip limit of rupture is of particular importance to the simulated ground motions in Seattle.





U20: 20-story steel moment-frame buildings designed according to U.S code.
B represents brittle welds and P represents perfect welds.

7. Nonlinear Responses of High-rise Buildings

The performance of 20-story steel moment frame buildings were simulated using Frame-2D which is a finite element program developed by J. Hall[9] at Caltech. It is based on a fiber-element model that includes both material nonlinearities as well as geometric nonlinearities. 4 types of buildings were considered. They are buildings designed according to UBC94 with brittle welds (U20B), perfect welds (U20P) and buildings designed according to Japanese building code published at 1987 with brittle welds (J20B), perfect welds (J20P).

The right figures show the peak interstory drift and maximum roof displacement for each rupture model. Our building simulations indicate that the buildings with brittle welds and perfect welds would collapse for rupture models where rupture extends beneath the Olympic Mountains. If slip is assumed to be limited to offshore regions (narrow model), U20B would collapse and U20P would be severely damaged.

From the time history figures shown in section 6, we found that the Seattle basin not only amplifies the ground motion amplitude but also elongates the duration. The strong shaking can last more than 4 minutes. In our simulation, buildings with brittle welds collapse even for the median and narrow models. Since our degradation model is very simple and local flange buckling is not considered, real high-rise buildings may perform significantly worse than our simulation. Even so, our simulations show that Seattle high-rise building with perfect welds have a significant potential for collapse.

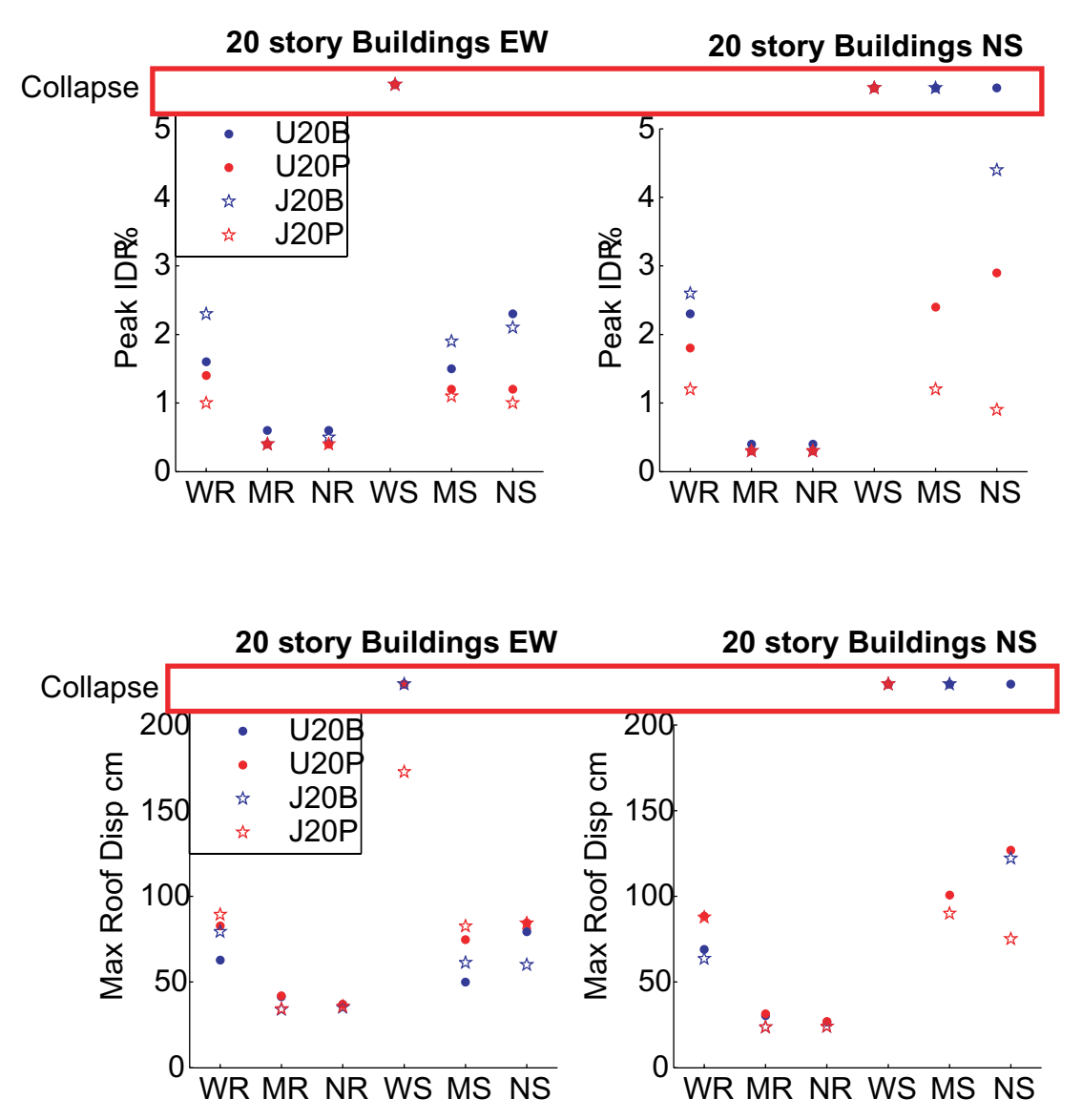


Figure: Peak Interstory Drift Ratio (IDR) and maximum roof displacement for each model. In the model names, R represents rock sites and S represents soil sites.

8. Conclusions

- The down-dip limit of rupture is of particular importance to the simulated ground motions in Seattle. Although simulated teleseismic p-waves are similar for wide, median and narrow models, the strong ground motions simulated from the wide model at rock sites can be 2-3 times larger than those simulated from the narrow model.
- Site amplification from the Seattle basin is very large in the frequency band 0.075 -1 Hz. In some cases, the amplitude ratio can be as large as 7. The Seattle basin also significantly elongates the shaking duration.
- Our building simulations indicate that the buildings with brittle welds and perfect welds would collapse for rupture models where rupture extends beneath the Olympic Mountains. If slip is assumed to be limited to offshore regions (narrow model), U20B would collapse and U20P would be severely damaged.
- The strong shakings have very long durations (more than 4 minutes), and our building simulations should be considered as a minimum estimate since we have used a very simple model of degradation of the structure.

Reference:

[1] Pratt and Brocher 2006 *Bull. Seismol. Soc. Am.* vol. 96. No. 2 pp. 536-552
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[4] Koketsu *et.al.* 2004 *Earth Planet Space 56* pp. 329-334
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[9] J. Hall 1997 *Technical Report EERL 97-05*