LONG-PERIOD BUILDING RESPONSE TO EARTHQUAKES IN THE SAN FRANCISCO BAY AREA

ANNA OLSEN, CALTECH ----- BRAD AAGAARD, USGS ----- TOM HEATON, CALTECH

ABSTRACT

We model long-period building responses to ground motion simulations of earthquakes in the San Francisco Bay area. The earthquakes include: scenarios of the 1989 Loma Prieta and 1906 San Francisco earthquakes; and two hypothetical magnitude 7.8 events on the northern San Andreas fault, each with a hypocenter north or south of San Francisco. The peak spectral accelerations from the 1906 scenario and the hypothetical earthquakes are larger than the design spectral values in the 2006 International Building Code. We use the simulated ground motions to excite nonlinear models of twenty-story, steel, special moment-resisting frame (SMRF) building models. We consider SMRF buildings designed with two different strengths and modeled with either ductile or brittle welds. Using peak inter-story drift ratio (PISDR) as a performance measure, the SMRF building responses in the Loma Prieta scenario are significantly smaller than those in the M 7.8 simulations. In the urbanized areas for the M 7.8 simulations, SMRF models with brittle welds show responses that threaten life safety on an area 5-10 times that of models with ductile welds. The hypothetical M 7.8 earthquake with a hypocenter north of San Francisco and north-to-south rupture causes large building responses on a greater area then the other two M 7.8 simulations. We use linear, single-degree of freedom models to estimate isolator displacements for base-isolated buildings. Many urbanized areas show isolator displacements in excess of 0.5 m for 10% damped, three-second isolator systems. This suggests that base-isolated structures must be designed with space to accommodate at least this much motion between the ground and structure.

METHOD

- We use long-period (T > 2 sec), simulated ground motions of scenario and hypothetical earthquakes, including: the 1989 Loma Prieta and 1906 San Francisco scenarios; and two hypothetical, M 7.8 northern San Andreas fault earthquakes.
- The M 7.8 hypothetical earthquakes have the same assumed slip distribution as the 1906 scenario, and each has a hypocenter either north (near Bodega Bay) or south (near San Juan Bautista) of San Francisco.
- The velocity model used to generate the ground motions limits shear wave speeds to greater than 700 m/s. Thus, there is no amplification of the ground motions due to soft soils.
- We apply the ground motions to examples of long-period building models, including: twenty-story, steel, special moment-resisting frame (SMRF) buildings; and base-isolation systems.
- We use SMRF models with two strengths — based on the 1992 Japanese Building Code (JBC) or 1994 Uniform Building Code (UBC) — and either ductile (P) or brittle (B) welds. The fundamental periods of the SMRF models are: 3.0 sec (J20P) and 3.5 sec (U20P). The base shears at yield normalized by design weight, V/W, are: 0.12 (J20P) and 0.09 (U20P).
- We perform a non-linear, time history analysis on the SMRFs, which includes: a non-linear, hysteretic steel model; P-Δ effects; planar frames oriented to bend about a building's weak axis; and the application of horizontal and vertical ground motions.
- We model base-isolation systems with isolator periods of 2 or 3 sec and isolator damping of 10% or 20% of critical.
- We assume the superstructure moves rigidly and the isolator period is 2-3 times the fundamental period of the superstructure. Therefore, we use spectral displacement to model isolator displacement
- Ryan and Chopra (2004) show that a linear isolator model, such as ours, underestimates the isolator displacement, compared to a non-linear model, by 10-30%.

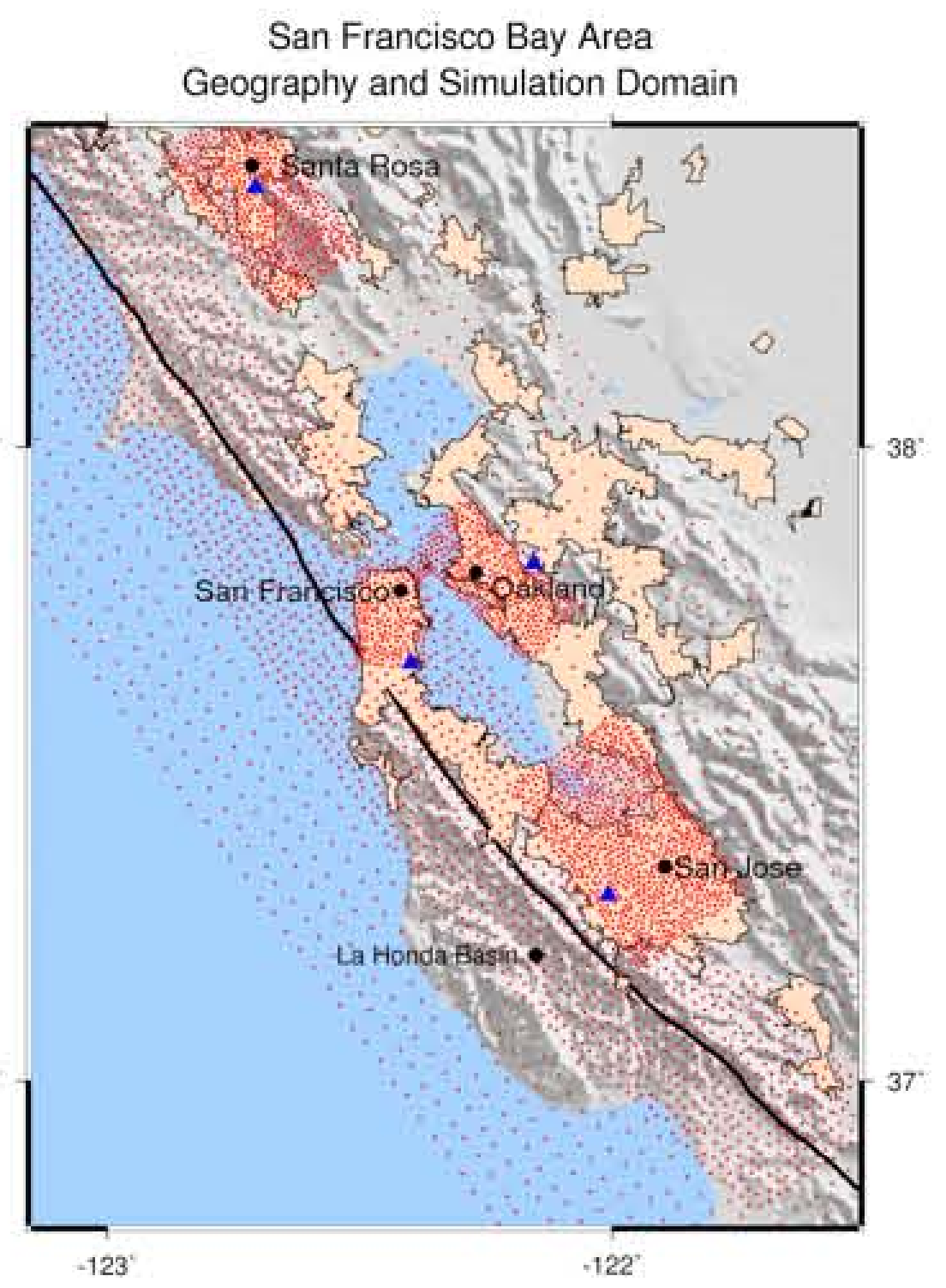

Figure 1. The San Francisco Bay area has a large urban area near the San Andreas fault (heavy black line). Light orange shading highlights the urban areas that include 97% of the region's population. (In other figures, a solid black line bounds the urban areas.) Red dots indicate the sites with simulated ground motion; some sites are located under water, but we do not include the results from these sites in our calculations. Blue triangles locate sites for response spectra presented in figure 11.

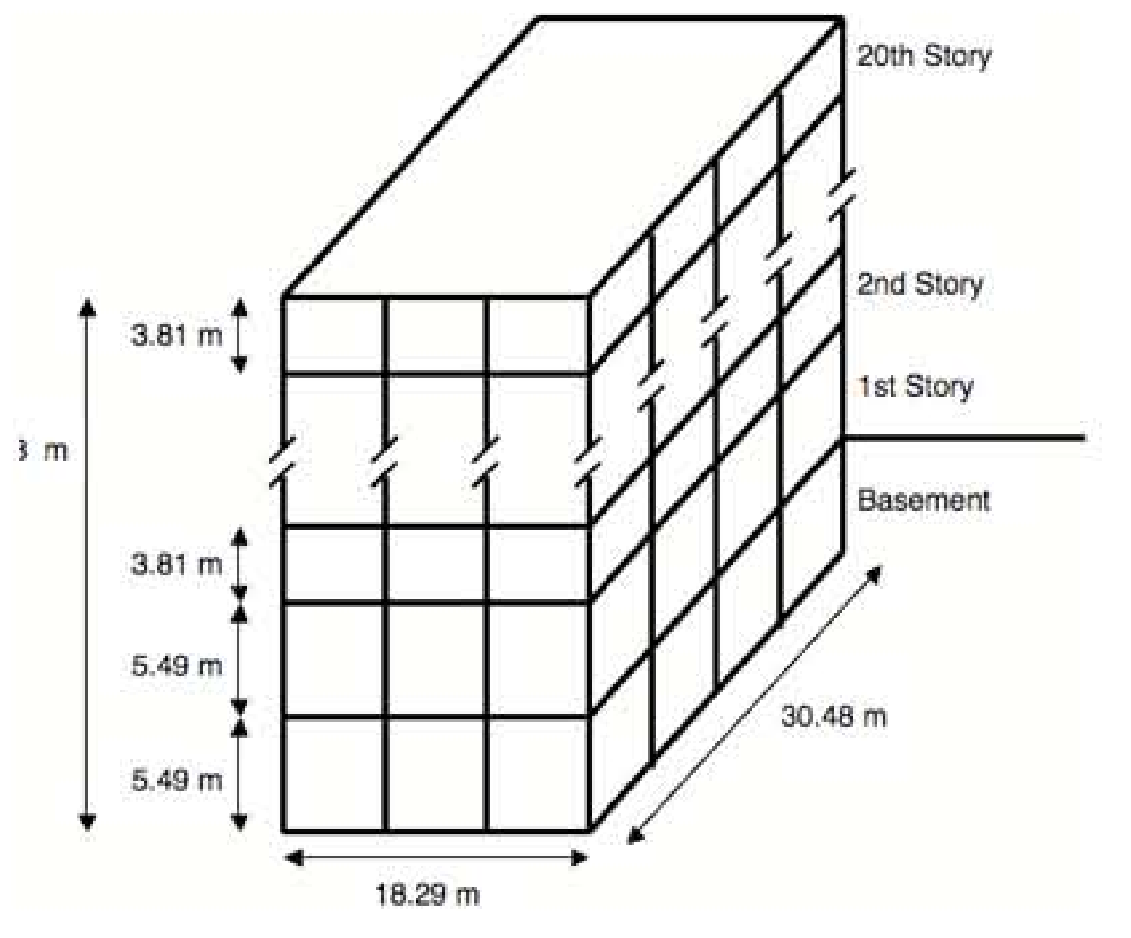

Figure 2. We use four, twenty-story, steel, SMRF building models in our analysis. The SMRF models share the same floor plan and dimensions. We consider SMRF models designed to the 1992 JBC or 1994 UBC provisions to evaluate the response of buildings with different strengths. We do not evaluate the building codes themselves nor suggest that buildings in the San Francisco Bay area were built to the JBC provisions. Also, the SMRF models have either ductile (non-fracturing) or brittle (fracturing) welds.

GROUND MOTIONS

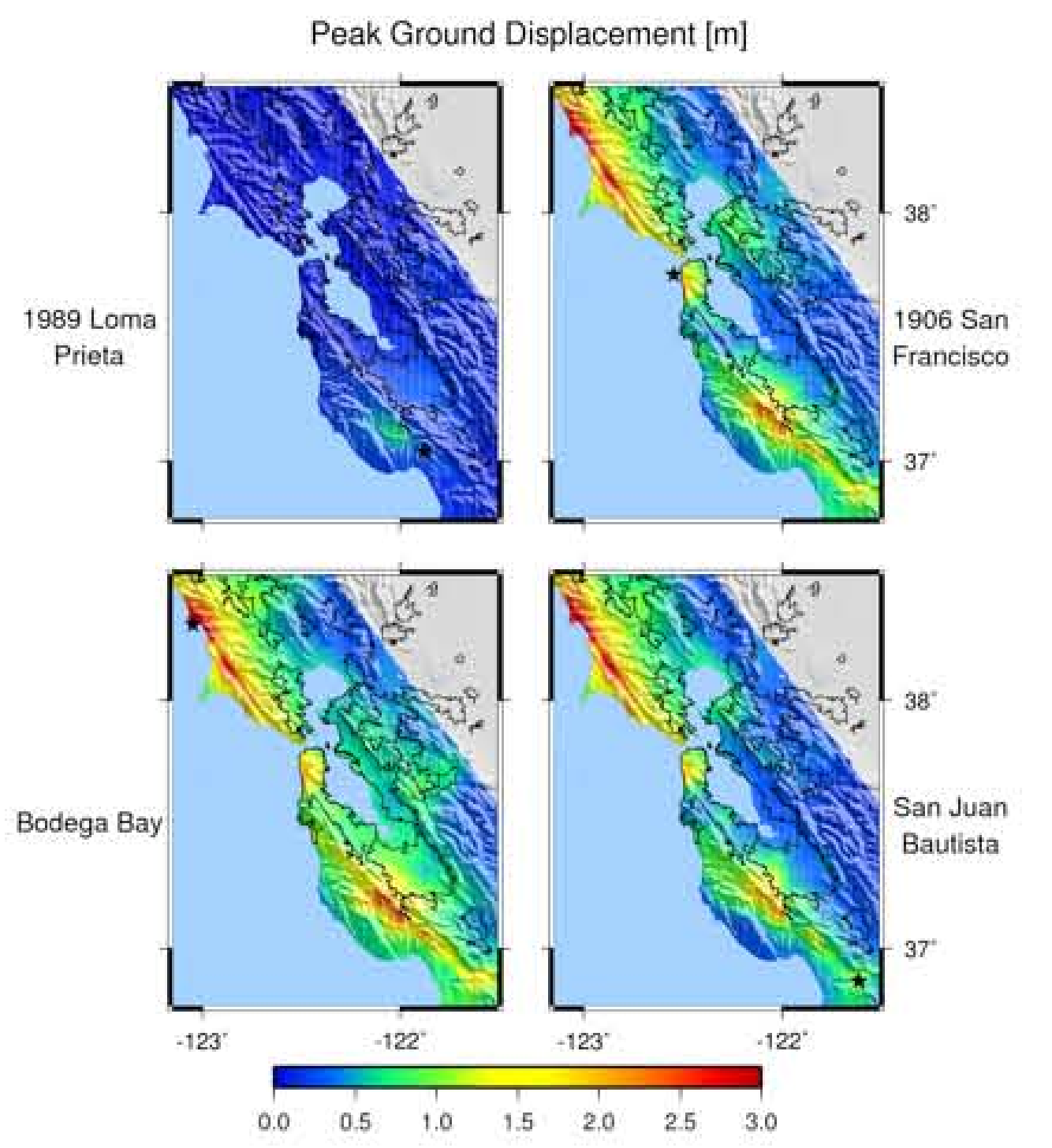

Figure 3. The largest peak ground displacement in the Loma Prieta scenario is 0.67 m. The peak ground motions in the magnitude 7.8 scenario and hypothetical earthquakes are significantly larger in amplitude and geographic extent. The largest peak ground displacements are: 4.24 m (M 7.8 Bodega Bay), 4.26 m (1906 San Francisco), and 4.29 m (M 7.8 San Juan Bautista).

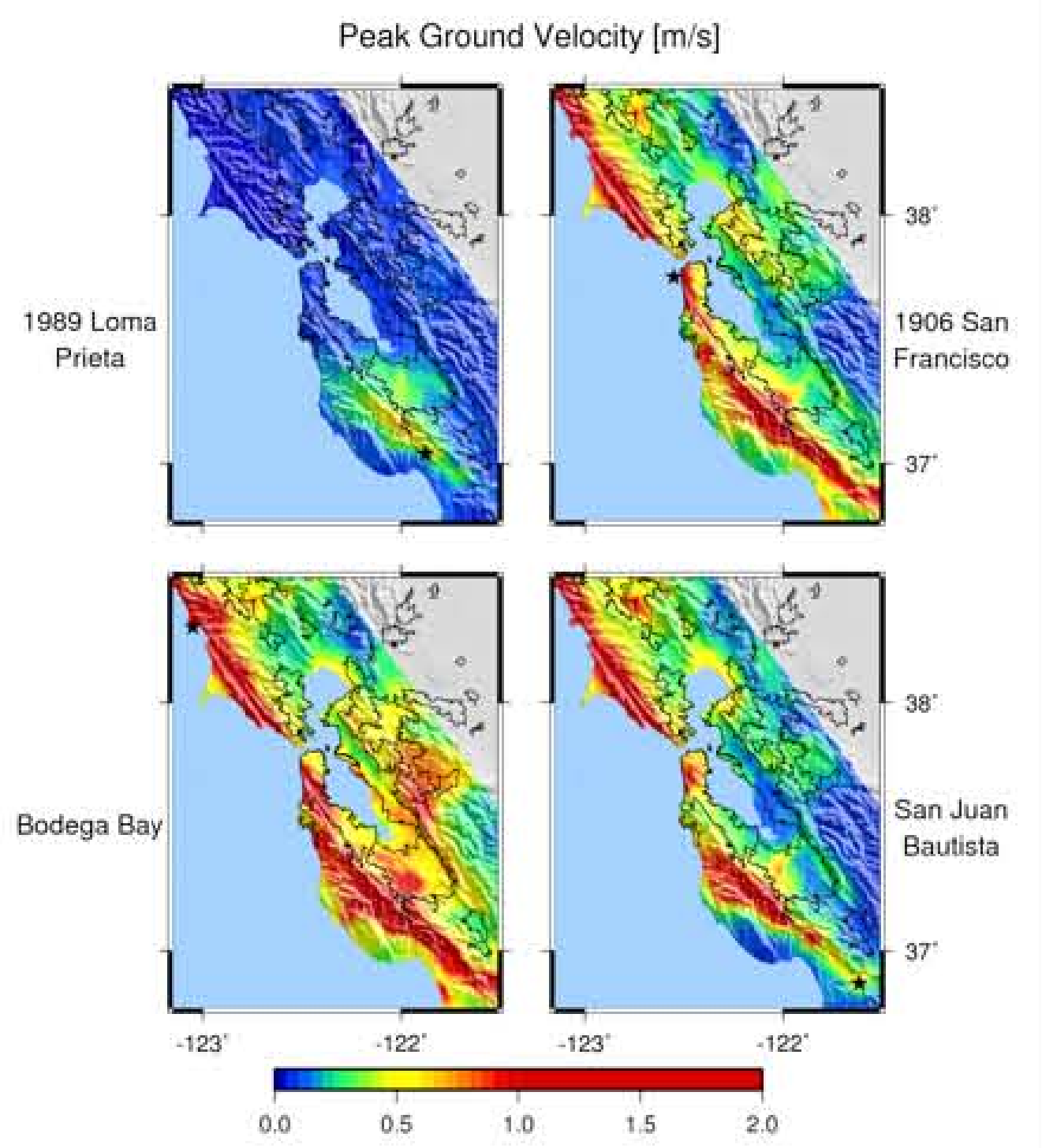

Figure 4. The three magnitude 7.8 earthquake simulations generate significantly larger peak ground velocities than those experienced in the 1989 Loma Prieta earthquake. The largest peak ground velocities are: 0.82 m/s (1989 Loma Prieta), 3.03 m/s (M 7.8 Bodega Bay), 3.85 m/s (1906 San Francisco), and 3.85 m/s (M 7.8 San Juan Bautista). The black stars locate the epicenters.

SMRF RESPONSES MAPPED

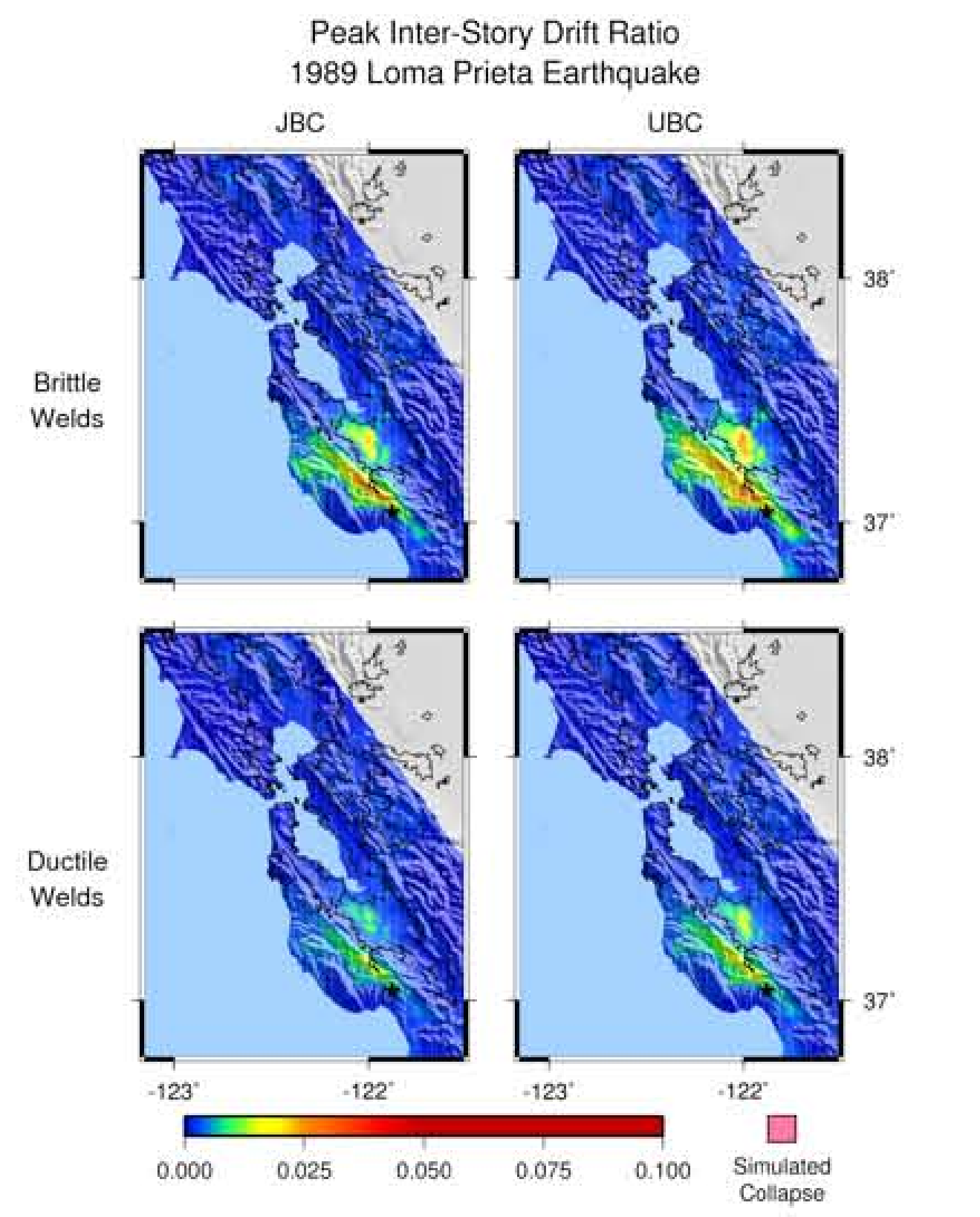

Figure 5. The 1989 Loma Prieta scenario earthquake induces small inter-story drifts in the SMRF building models. The largest building responses would have been observed in the urban area of the Santa Clara Valley, near San Jose.

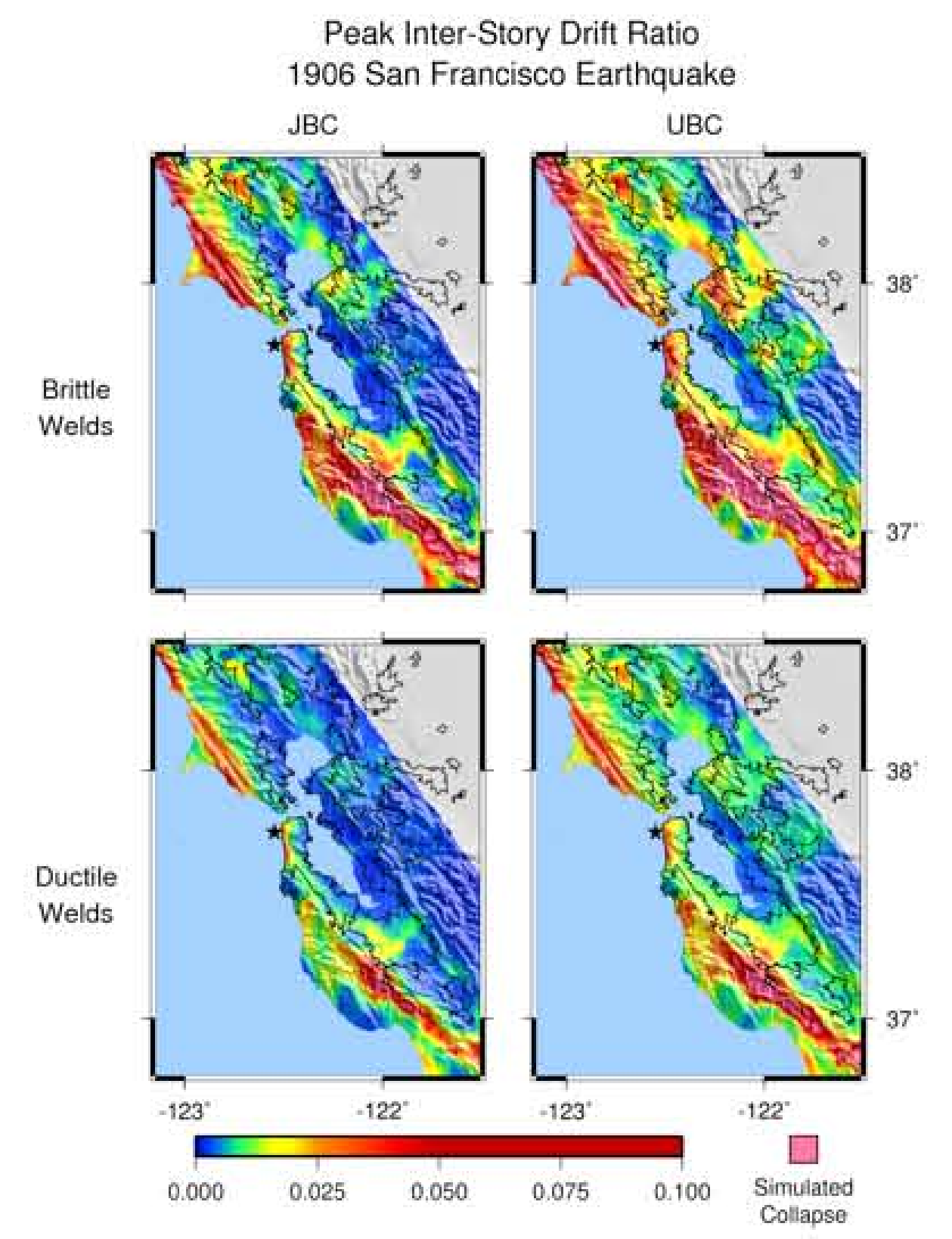

Figure 6. This simulation predicts SMRF building responses in the 1906 San Francisco scenario earthquake. The hypocenter is located offshore and west of San Francisco, and the fault ruptures bilaterally. Most energy travels away from the city of San Francisco; of the three magnitude 7.8 scenario and hypothetical earthquakes, this scenario tends to show the smallest responses in San Francisco.

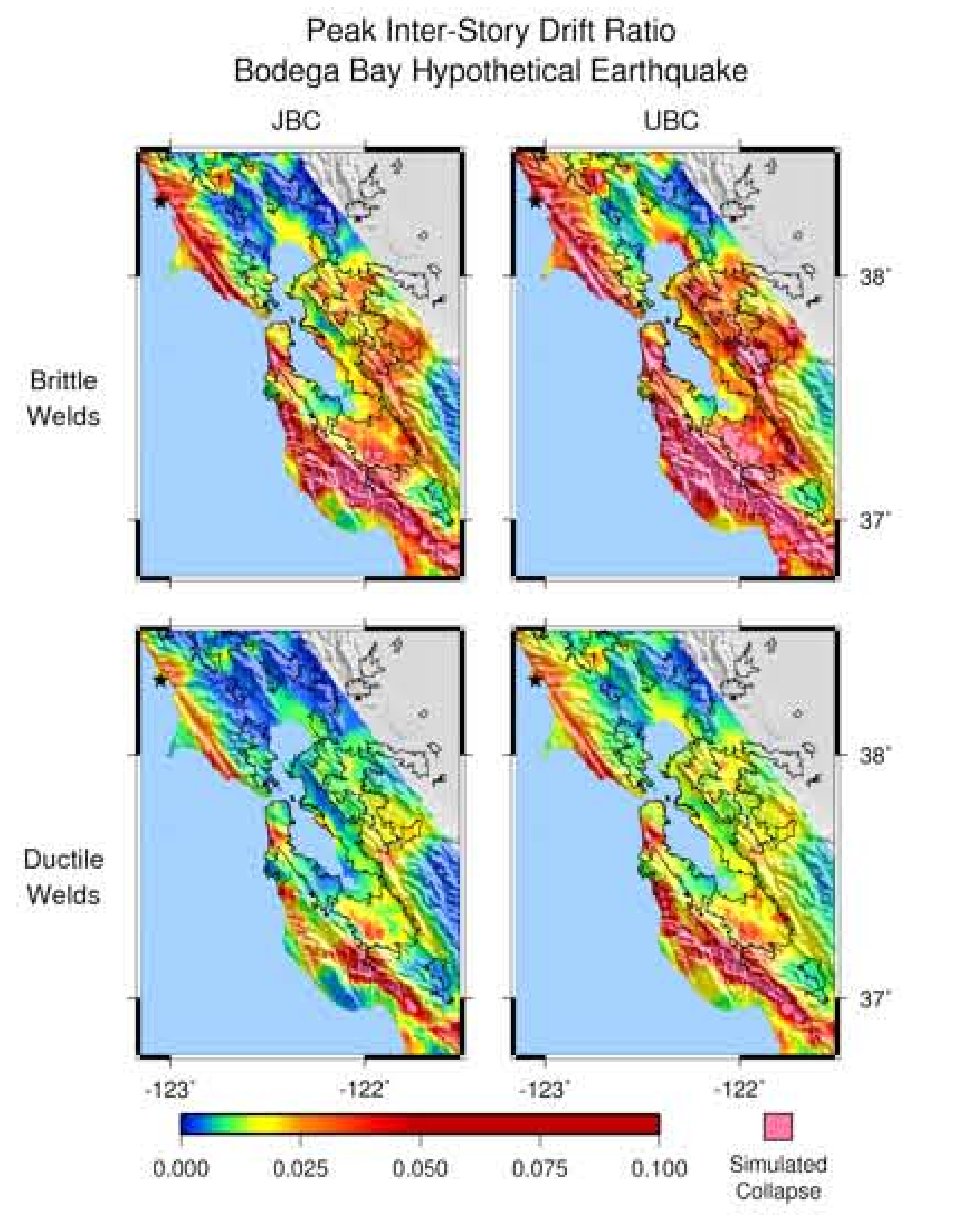

Figure 7. In the M 7.8 Bodega Bay hypothetical earthquake, the rupture propagates north-to-south into the San Francisco Bay area. Urban areas south of San Francisco and Oakland show large steel SMRF building model responses. As in all scenarios, SMRF models designed to the JBC outperform the equivalent UBC model, and buildings with ductile welds outperform those with brittle welds.

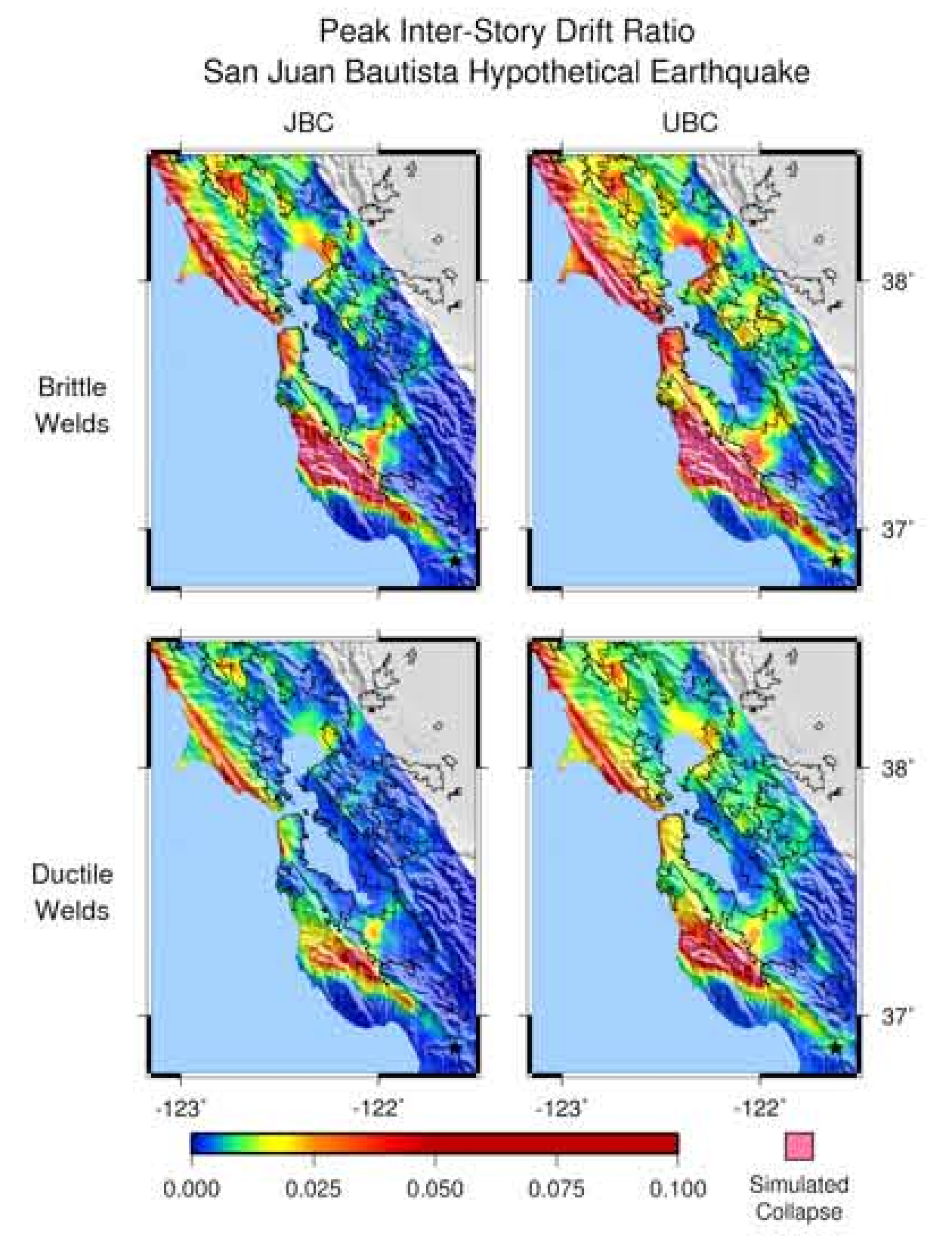

Figure 8. Considering the urban area in the magnitude 7.8 San Juan Bautista hypothetical earthquake, the largest building responses occur in San Francisco. Urban areas outside San Francisco tend to have the smallest responses of all three magnitude 7.8 earthquakes. This scenario produces the fewest simulated collapses in the urban areas.

BASE-ISOLATOR RESPONSES

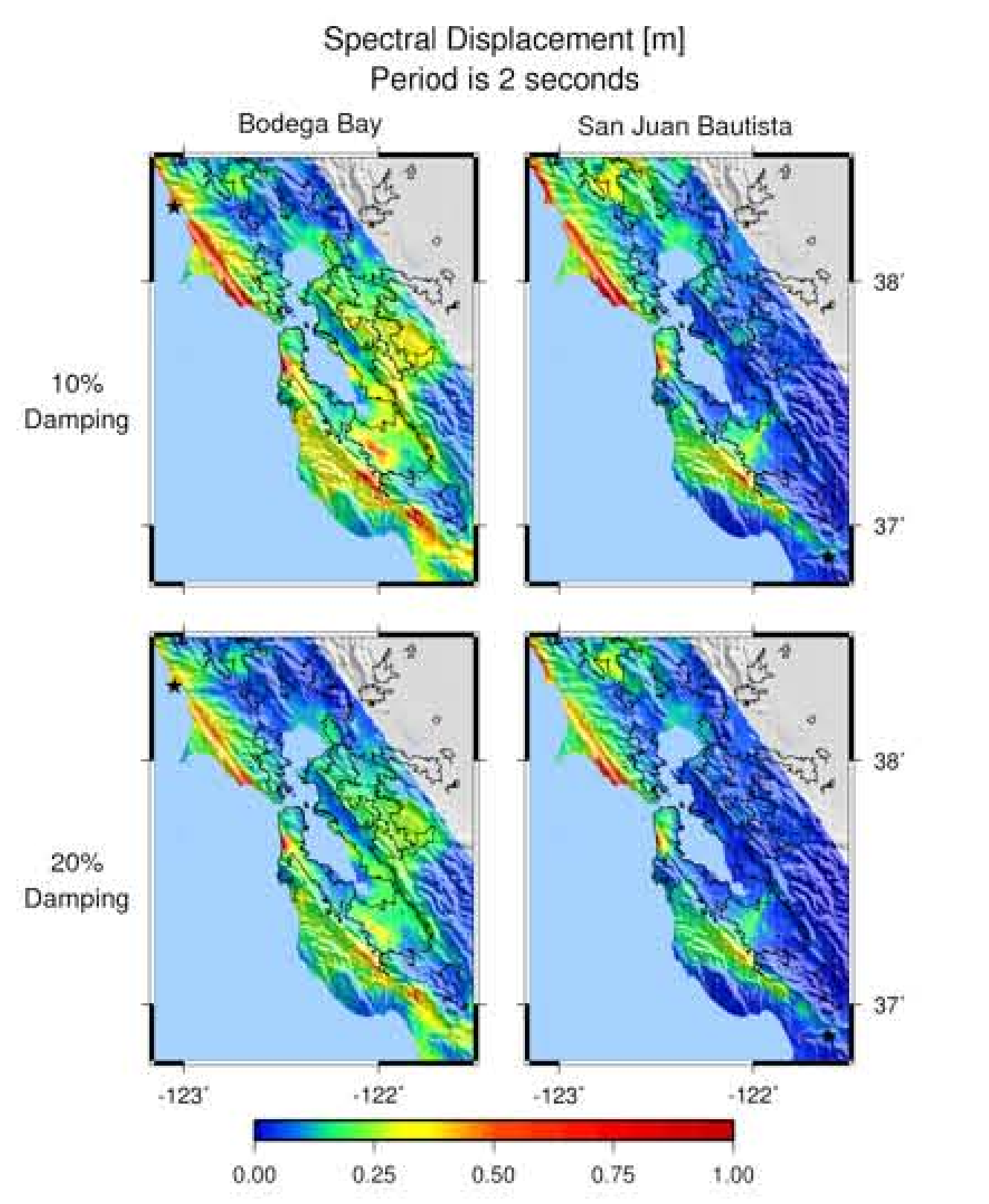

Figure 9. For linear isolators with a fundamental period of two seconds, the predicted maximum isolator displacements are large on most of the San Francisco Bay area in the two magnitude 7.8 hypothetical earthquakes. Existing base-isolation systems may not be designed for isolator displacements this large. Also, the isolator displacements from linear models are lower bounds compared to displacements from more realistic, non-linear simulations. (Note coloring scheme is different than figure 10.)

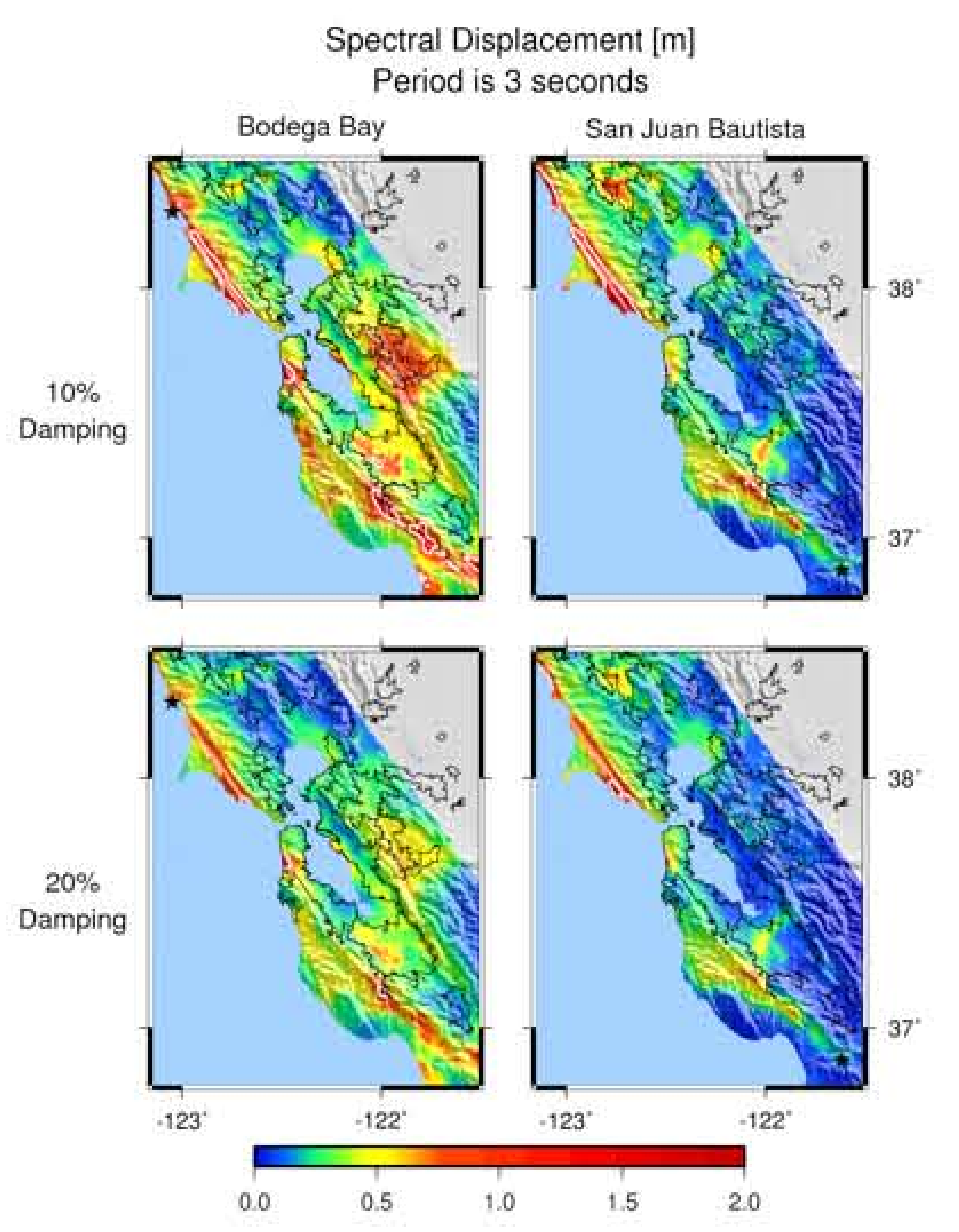

Figure 10. The M 7.8 hypothetical earthquakes induce large isolator displacements in linear, three-second isolators, and the three-second isolators give large displacements on a greater area than the two-second isolators. Large damping reduces the peak isolator displacements. (Note coloring scheme is different than figure 9. The white contour is a peak isolator displacement of 1 m, whereas the design maximum displacement of three-second isolators are typically near 0.5 m.)

RESPONSE SPECTRA

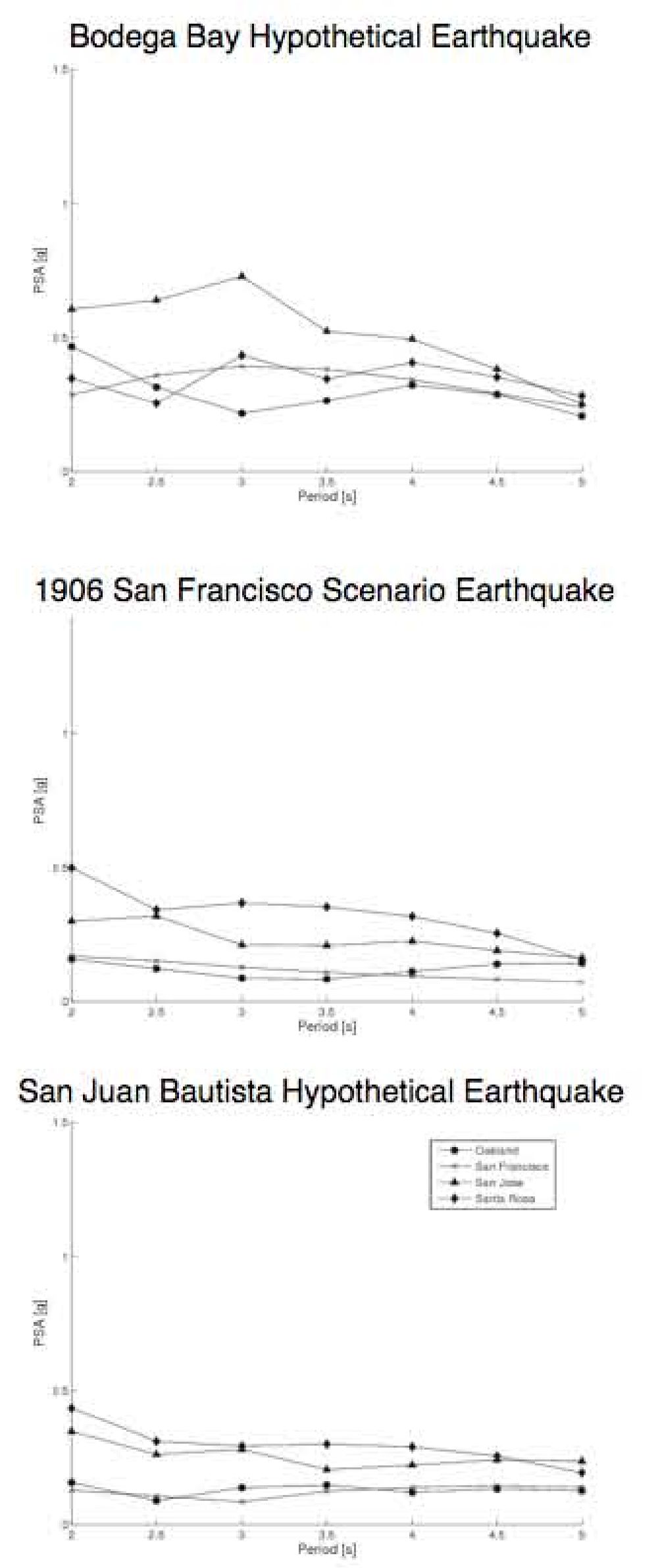

Figure 11. This figure shows standard response spectra at four sites in the San Francisco Bay area for each magnitude 7.8 simulated earthquake. For each sub-domain of the major cities we consider, we present the response spectra at a site with large pseudo-spectral acceleration (PSA) at three-seconds. Figure 1 locates the four sites with blue triangles. The energy content of our ground motions is limited to frequencies of 0.5 Hz and lower; the filter likely removes some energy at two-seconds, resulting in the flat response spectral values at that period.

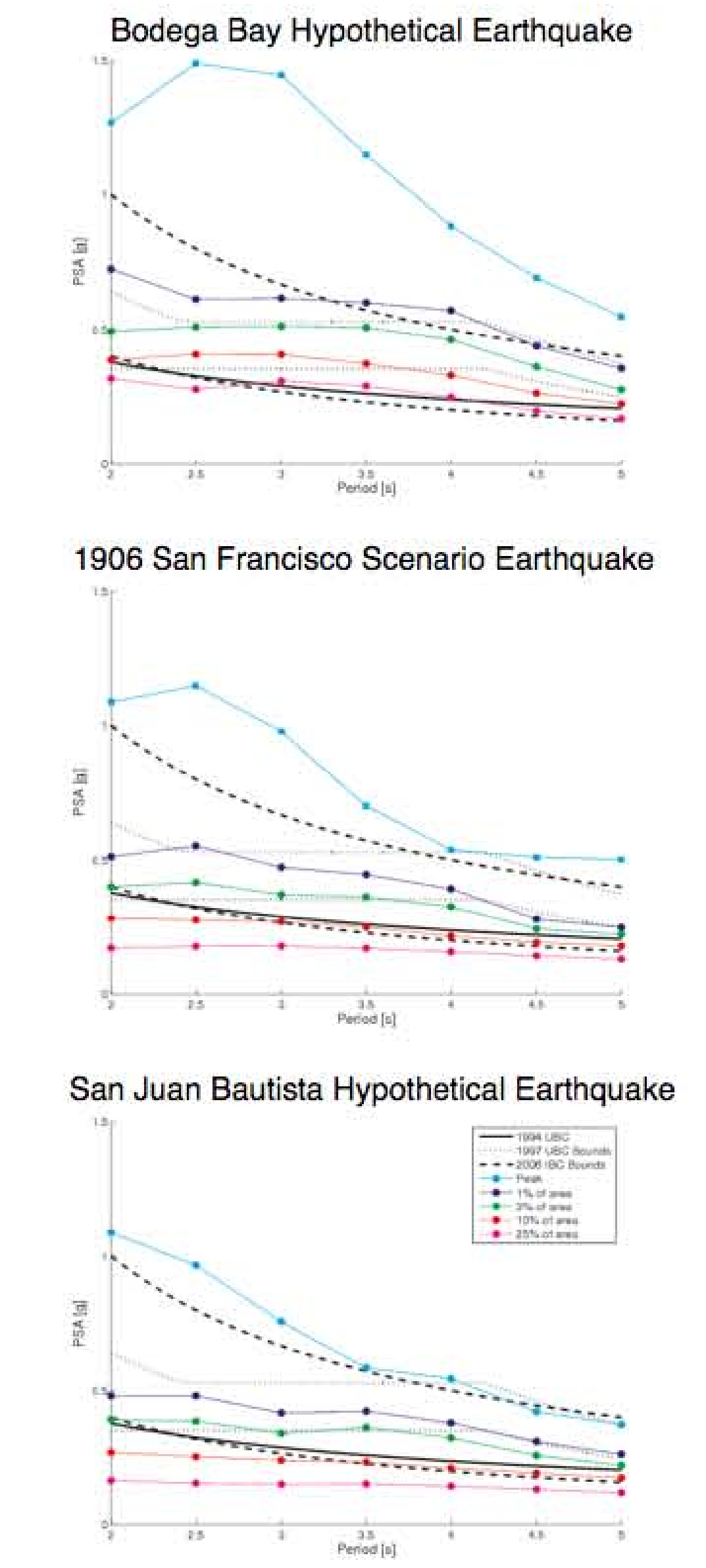

Figure 12. Due to the large number of sites in this study, we group the response spectra according to the urban area on which the ground motions exceed a certain pseudo-spectral acceleration (PSA). For example, in the 1906 San Francisco simulation, ground motions on 1% of the urban area exceed approximately 0.5 g for periods of 2-3 seconds. We compare these response spectra for the simulated ground motions to the design spectra of the 1994 and 1997 UBC and of the 2006 IBC. The design spectra at a specific site in the San Francisco Bay area lies between the upper and lower bounds of the 1997 UBC and 2006 IBC design spectra in this figure. The peak spectral accelerations in all three simulations exceed the upper bound of the 2006 IBC design spectra.

SMRF RESPONSES TABULATED

Areas in Urban Outline [%] that Exceed PISDR of 0.025	*J20B*	*J20P*	*U20B*	*U20P*
1989 Loma Prieta	0.092	0	0.31	0
M 7.8 Bodega Bay	30.	4.7	53	10.
1906 San Francisco	7.6	1.0	16	3.2
M 7.8 San Juan Bautista	9.5	0.98	17	2.8
Areas in Oakland [%] that Exceed a PISDR of 0.025				
1989 Loma Prieta	0	0	0	0
M 7.8 Bodega Bay	16	1.6	48	0.20
1906 San Francisco	0	0	0	0
M 7.8 San Juan Bautista	0	0	0	0
Areas in San Francisco [%] that Exceed a PISDR of 0.025				
1989 Loma Prieta	0	0	0	0
M 7.8 Bodega Bay	42	18	69	35
1906 San Francisco	30.	12	49	18
M 7.8 San Juan Bautista	51	6.8	92	13
Areas in San Jose [%] that Exceed a PISDR of 0.025				
1989 Loma Prieta	0.028	0	1.7	0
M 7.8 Bodega Bay	59	11	83	26
1906 San Francisco	12	0.18	18	3.8
M 7.8 San Juan Bautista	8.8	0.51	14	1.6
Areas in Santa Rosa [%] that Exceed a PISDR of 0.025				
1989 Loma Prieta	0	0	0	0
M 7.8 Bodega Bay	12	0	38	3.1
1906 San Francisco	21	0	25	8.6
M 7.8 San Juan Bautista	34	5.7	27	11

Areas in Urban Outline [%] with Simulated Collapse	*J20B*	*J20P*	*U20B*	*U20P*
1989 Loma Prieta	0	0	0	0
M 7.8 Bodega Bay	1.1	0.061	6.7	0.21
1906 San Francisco	0.31	0	0.83	0
M 7.8 San Juan Bautista	0.031	0	0.64	0
Areas in Oakland [%] with Simulated Collapse				
1989 Loma Prieta	0	0	0	0
M 7.8 Bodega Bay	0	0	0	0
1906 San Francisco	0	0	0	0
M 7.8 San Juan Bautista	0	0	0	0
Areas in San Francisco [%] with Simulated Collapse				
1989 Loma Prieta	0	0	0	0
M 7.8 Bodega Bay	6.2	0.89	24	4.1
1906 San Francisco	0	0	1.8	0
M 7.8 San Juan Bautista	0	0	1.3	0
Areas in San Jose [%] with Simulated Collapse				
1989 Loma Prieta	0	0	0	0
M 7.8 Bodega Bay	1.8	0	15	0.033
1906 San Francisco	0	0	0.97	0
M 7.8 San Juan Bautista	0	0	0.59	0
Areas in Santa Rosa [%] with Simulated Collapse				
1989 Loma Prieta	0	0	0	0
M 7.8 Bodega Bay	0	0	4.0	0
1906 San Francisco	0	0	0	0
M 7.8 San Juan Bautista	0	0	0.069	0

Table 1. FEMA 356 defines a level of "life safety" for steel SMRF buildings at an inter-story drift ratio of 0.025. At this level, a building would require structural repairs, but partial or total collapse is unlikely. Depending on the earthquake and building type, the simulated building responses may exceed the "life safety" level on a limited or broad portion of the urban area. The Bodega Bay hypothetical earthquake especially causes damage in large parts of the San Francisco Bay urban area. The entire urban area in the simulation domain is 3266 km^2.

Table 2. Some ground motions cause exceedance of the lateral force resisting ability of the SMRF models ("simulated collapse"). This level is much greater than the "life safety" performance level defined by FEMA 356. SMRF models with brittle welds show simulated collapses on a greater area than models with ductile welds. Models designed to the lateral force requirements of the 1992 JBC outperform models designed to the 1994 UBC.

CONCLUSIONS

- The long-period buildings we choose to study show simulated responses that approach and reach failure on a large area in M 7.8 earthquake simulations. The steel SMRF models' responses in the 1989 Loma Prieta scenario are considerably smaller than those of the large magnitude simulations. A long-period building that withstood the ground motions in the 1989 Loma Prieta earthquake may experience significant damage in an event like the 1906 San Francisco earthquake. For all steel SMRF building models, the building responses in the 1989 Loma Prieta scenario exceed the "life safety" level on no more than 0.3% of the urban area, compared to 1-53% for the M 7.8 simulations. Additionally, the variability in the long-period building models' responses at a single site to the three M 7.8 simulations implies a large range of possible building responses, depending on the rupture direction.

- The design of steel SMRF building affects the likelihood of large response. For the same ground motion, SMRF models designed with the lateral force requirements of the 1992 JBC outperform their equivalent design according to the 1994 UBC. Increasing the lateral force requirement from the 1994 UBC to the 1992 JBC, decreases the area of simulated collapse by a factor of 3-6. Our modeling suggests that buildings with brittle welds are vulnerable to long-period ground motions from large earthquakes on the San Andreas fault. Fixing brittle welds decreases the area of simulated collapse by a factor of 20-30 or increases the likelihood of no simulated collapses.

- Since the ground motion simulations limit the minimum shear wave speed to 700 m/s, the ground motions do not include the amplification associated with soft, near-surface sediments and artificial fill. Consequently, the predictions of building response in areas of soft sediments or poorly compacted fill may be considered lower bounds. Thus, we expect the extent of large building response in the urban areas could be greater than we predict in the event of another great earthquake in the San Francisco Bay area.

- In these ground motions, equivalent-linear models of base-isolated buildings show conservative estimates of isolator displacements of 0.4-1 m. Local site amplification and non-linear isolator behavior---not included in the ground motion and building models, respectively---would tend to increase the predicted estimates of base isolator displacements. Since important government buildings, hospitals, and communication centers must remain functional after a large earthquake, engineers should consider large ground motions, like the ones used in the study, when designing isolation systems for these types of buildings.

- The peak spectral accelerations from the three M 7.8 earthquakes exceed the upper bound of the 2006 IBC design spectra. On 10-25% of the urban area the spectral accelerations from the simulations exceed the lower bound of the current design spectrum. We conclude that some ground motions from these earthquakes exceed the current design spectra, but this conclusion is limited since we do not account for the uncertainties in generating the ground motions. Future simulations that account for the variability in slip distribution, hypocenter location, etc, can provide additional information on the adequacy of the design spectra and MCE level defined in the 2006 IBC.

ACKNOWLEDGMENTS

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