Chapter 5

Simulations of Distant Earthquakes

This chapter studies the responses of twenty-story steel moment-resisting frames to simulated magnitude 7.7 and 7.8 ruptures on the southern San Andreas fault. The simulated earthquakes include the ShakeOut scenario earthquake and the two sets of TeraShake scenario earthquakes. The ground motions used in the previous chapters are primarily near-source; in this chapter, the ground motions are mostly characterized by long-period amplification in sedimentary basins. Despite the different character of the ground motions, the building responses as functions of peak ground velocity are consistent with results in previous chapters. This chapter also considers the permanent total drift response of the steel moment frames.

5.1 Ground Motion Studies

To prepare residents of southern California for the next great earthquake, the United States Geological Survey developed a year-long program to study and improve earthquake preparedness and response. Hudnut et al. (2007) defined a source model for a magnitude 7.8 scenario earthquake on the southern San Andreas fault. This earthquake ruptures the fault segments that last broke in 1680, 1812, and 1857, which are east and north of Los Angeles. Several groups simulated ground motions from this source model to provide plausible descriptions of the shaking in the Los Angeles area (for example, Graves et al. (2008)). Chen Ji used the Harvard version of the Southern California Earthquake Center Community Velocity Model (Süss and Shaw,

Version	*Rupture*	*Slip distribution*
1.2	NW to SE, sub-shear	Denali, original slip
1.3	SE to NW, sub-shear	Denali, original slip
1.4	SE to NW, sub-shear	Denali, mirrored slip
2.1	SE to NW, super-shear	from low initial stress
2.2	SE to NW, sub-shear	from medium initial stress
2.3	NW to SE, sub-shear	from high initial stress

Table 5.1: Olsen et al. (2006, 2007) generated three scenario earthquakes each for TeraShake 1 and 2. The TeraShake 1 scenarios differ in the orientation of the assumed slip distribution and the direction of rupture propagation. The TeraShake 2 scenarios differ in the assumed three-dimensional state of stress at the fault plane as well as the direction of rupture propagation.

2003) to generate long-period ground motions for this scenario. Figure 5.1 maps the long-period peak ground displacements and velocities for the entire simulation domain and for a sub-domain centered on the Los Angeles metropolitan area. Near the fault, the long-period peak ground displacements are approximately 3 m, and some long-period peak ground velocities exceed 3 m/s.

In a separate research effort, Olsen et al. (2006, 2007) generated two series of earthquakes on the southern San Andreas fault, called TeraShake 1 and 2. These scenario earthquakes rupture the southern San Andreas segments that produced the 1680 and 1812 earthquakes. TeraShake 1 used a kinematic source model with a final slip distribution based on the Denali earthquake, whereas TeraShake 2 used a dynamic source model. Each set of TeraShake simulations had three distinct ruptures: one rupture propagates from the northwest to the southeast; and two ruptures propagate from the southeast to the northwest. For TeraShake 1 the assumed slip distribution is mirrored for one of the southeast-to-northwest ruptures. The seismic wave speed model for both sets of TeraShake simulations is Version 3.0 of the Southern California Earthquake Center Community Velocity Model, and the period content of the ground motions is periods greater than 2 s. Table 5.1 summarizes the TeraShake ruptures. Figures 5.2 and 5.3 map the long-period peak ground displacements and velocities for TeraShake 1 and 2, respectively.

The predicted ground motions in the TeraShake 2 simulations are notably different

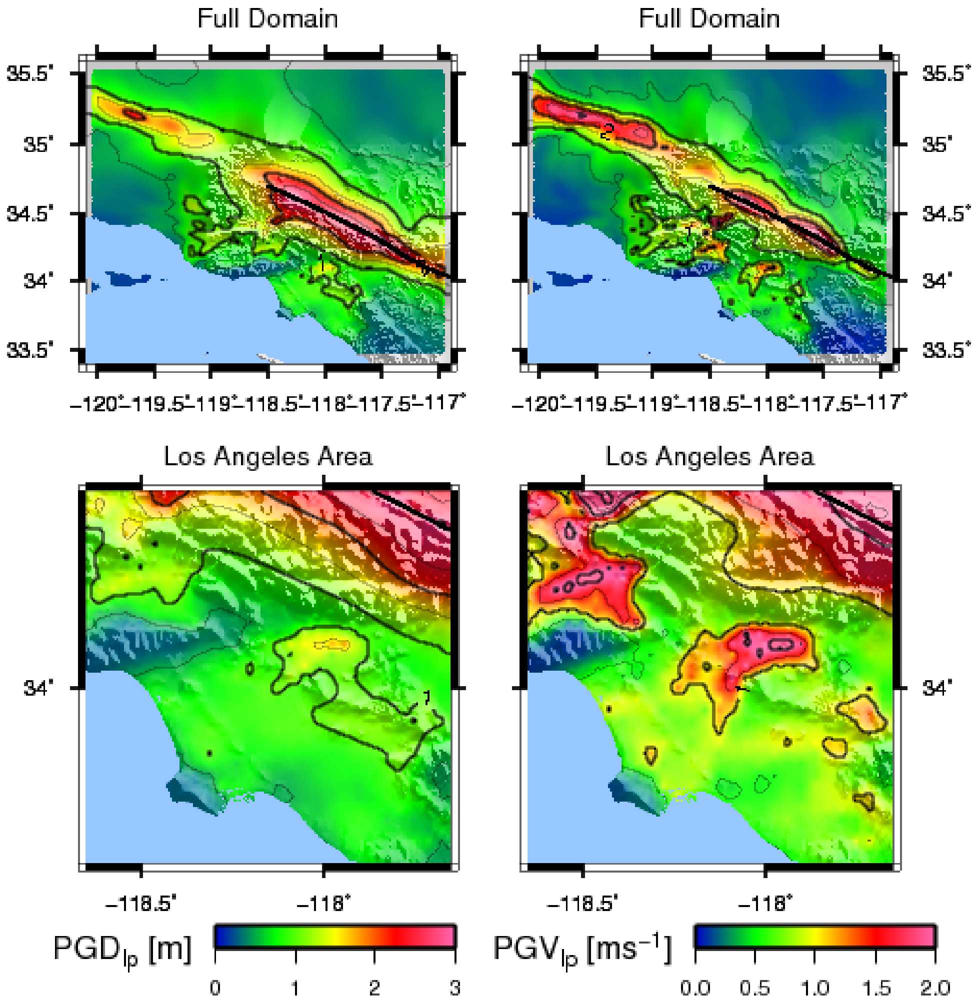

Figure 5.1: The ShakeOut simulation on the southern San Andreas fault ruptures from the southeast to the northwest. The top maps show the peak ground measures for the entire simulation domain, and the bottom maps show them for the Los Angeles metropolitan area.

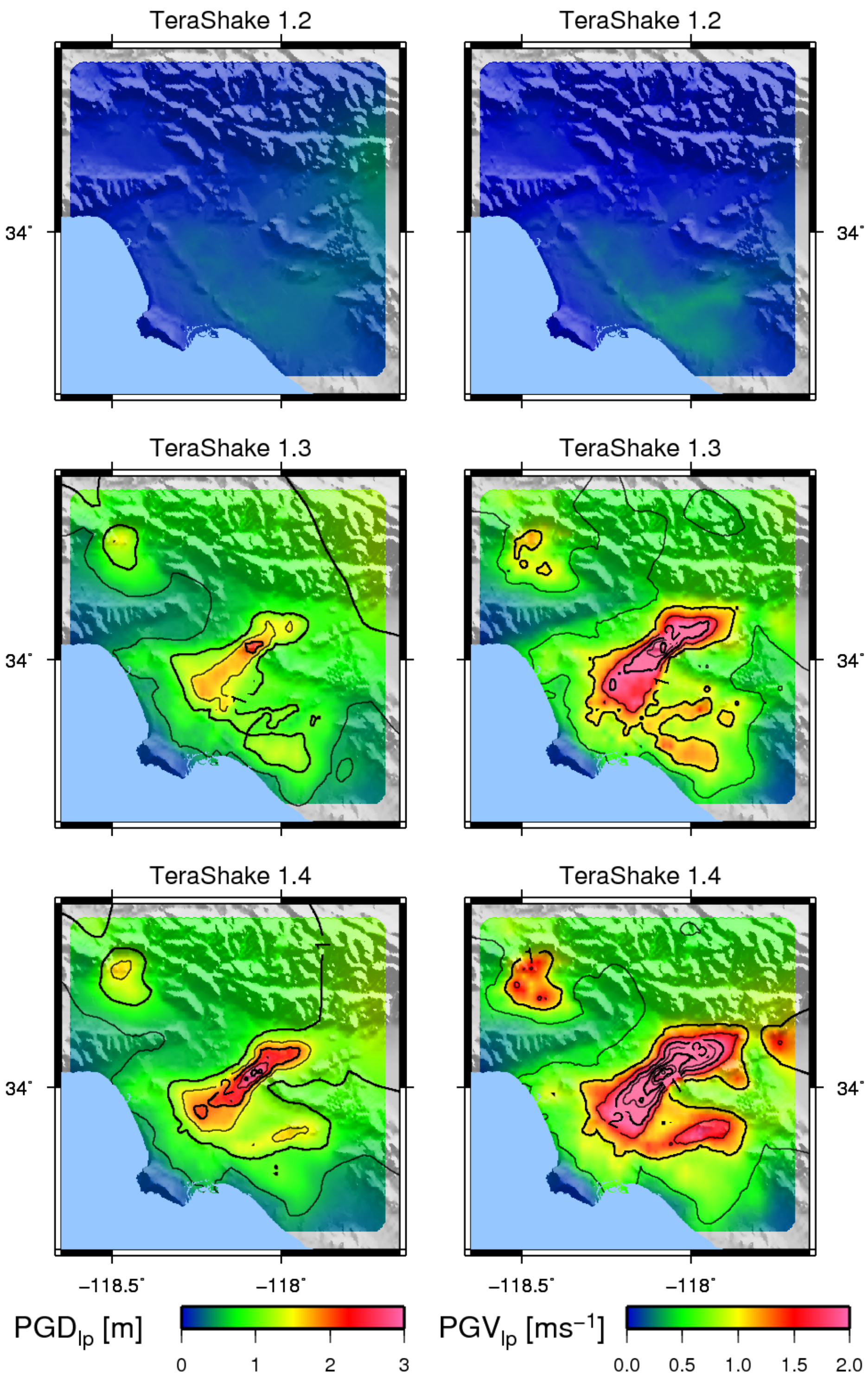

Figure 5.2: The TeraShake scenario earthquakes simulate the ground motions in a magnitude 7.7 rupture of the southern San Andreas fault. TeraShake 1 uses a kinematic source model of rupture propagation on the fault. The resulting ground motions in the Los Angeles basin are large.

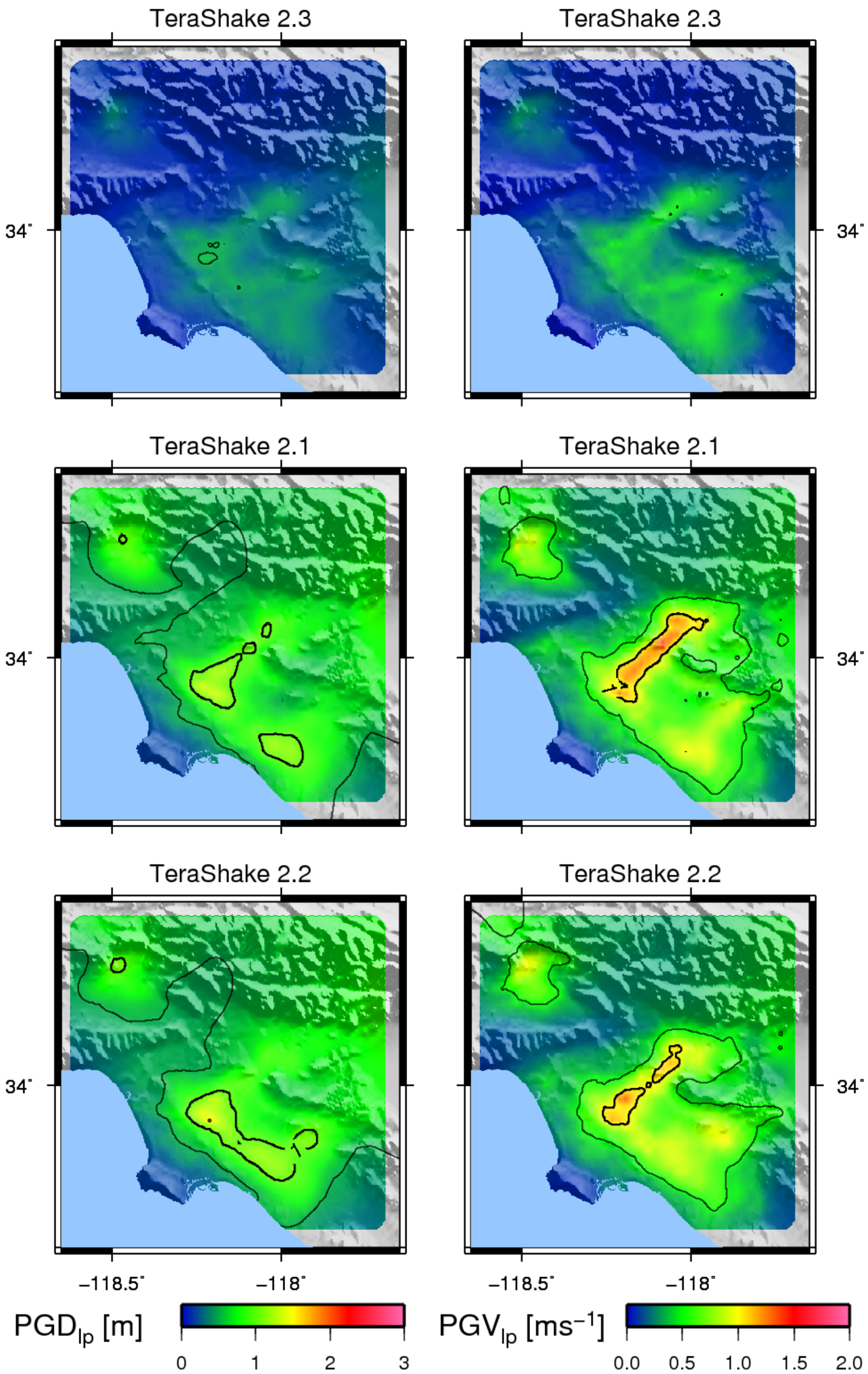

Figure 5.3: TeraShake 2 uses a dynamic source model of rupture propagation on the fault. Compared to the peak ground displacements and velocities in TeraShake 1, the ground motions predicted by TeraShake 2 are smaller. Nonetheless the long-period peak ground displacement is greater than 0.5 m in most of the Los Angeles area, and the long-period peak ground velocity exceeds 1 m/s throughout the Los Angeles basin.

than those in TeraShake 1 due to the type of source model (that is, dynamic or kinematic, respectively). A kinematic source model assumes a final slip distribution, a rupture velocity description, and a slip velocity function. Thus the evolution in time of slip at every location on the fault is modeled directly and explicitly. A dynamic source model defines the state of stress and the friction law in the media near the fault plane. Then the rupture is artificially initiated at the hypocenter. Olsen et al. (2007) sought initial stress distribution and friction law parameter values that resulted in primarily sub-shear rupture propagation. The initial shear stress distribution was based on a previous study of the magnitude 7.3 1992 Landers earthquake and scaled to be consistent with a magnitude 7.7 event. The peak ground displacements and velocities in TeraShake 1 are larger than those in TeraShake 2; the peak ground velocities in TeraShake 2.1 and 2.2 are generally twice as large as those in TeraShake 1.3 and 1.4, respectively.

TeraShake 2 represents the current state of the art for simulation of ground motion time histories. Since TeraShake 2 has a complex source model, the resulting seismic waves are less coherent than those generated by the simpler, TeraShake 1 source model (Olsen et al., 2007). A less coherent wavefront produces lower peak ground displacements and velocities. Furthermore, the ShakeOut simulation used a kinematic source model; peak ground displacements and velocities from a ShakeOut simulation with a dynamic source model would be smaller. Unfortunately, there is little data available to validate earthquake simulations with such large fault slips.

This thesis simulates building responses in the TeraShake 1, TeraShake 2, and ShakeOut (with kinematic source model) simulations. Although the ground motions from the kinematic source models of these magnitude 7.7 and 7.8 earthquakes may be implausibly large, they are available for study. Chapter 6 develops building response prediction models from intensity measures, and these unusually large ground motions contribute to the definition of the prediction models by providing data at large intensities.

5.2 Permanent Total Drift

This section presents the building responses as measured by the permanent total drift ratio (PTDR). In the two previous chapters, the peak inter-story drift ratio measures the building response, which characterizes the dynamic building response and demonstrates collapse. As discussed in Section 2.4, the permanent total drift ratio measures the static offset of the building following the dynamic earthquake excitation. Figure 5.4 maps the permanent total drift ratio for the twenty-story building models in the TeraShake 1.3, TeraShake 2.1, and ShakeOut simulations. The relative building performance of the twenty-story buildings is the same when measured by peak inter-story drift or by permanent total drift: the stiffer, higher-strength design has smaller building responses compared to the more flexible, lower-strength design; and the presence of brittle welds significantly increases the building response compared to buildings with perfect welds.

The areal extent of large permanent total drifts depends on the type of source model (that is, kinematic or dynamic) used to generate the simulated ground motions. Figure 5.4 maps the permanent total drift ratios of the twenty-story models in the TeraShake 1.3, TeraShake 2.1, and ShakeOut simulations. The simulations with kinematic source models (TeraShake 1.3 and ShakeOut) show large permanent drifts throughout the Los Angeles basin; the simulation with a dynamic source model (TeraShake 2.1) induces large permanent drifts on more limited parts of the Los Angeles basin. Nonetheless the TeraShake 2.1 simulation shows that a distant earthquake on the southern San Andreas fault induces large permanent drifts in twenty-story buildings located in the Los Angeles area.

Figure 5.5 compares the three measures of building response for the simulations on the southern San Andreas fault. The curves that show the proportions of collapse and total structural loss as functions of peak ground velocity are quite close for the twenty-story building models. For a small increase in peak ground velocity, the expected building response is collapse instead of total structural loss. Peak ground velocity must increase by 0.3–1 m/s to change the expected building response from

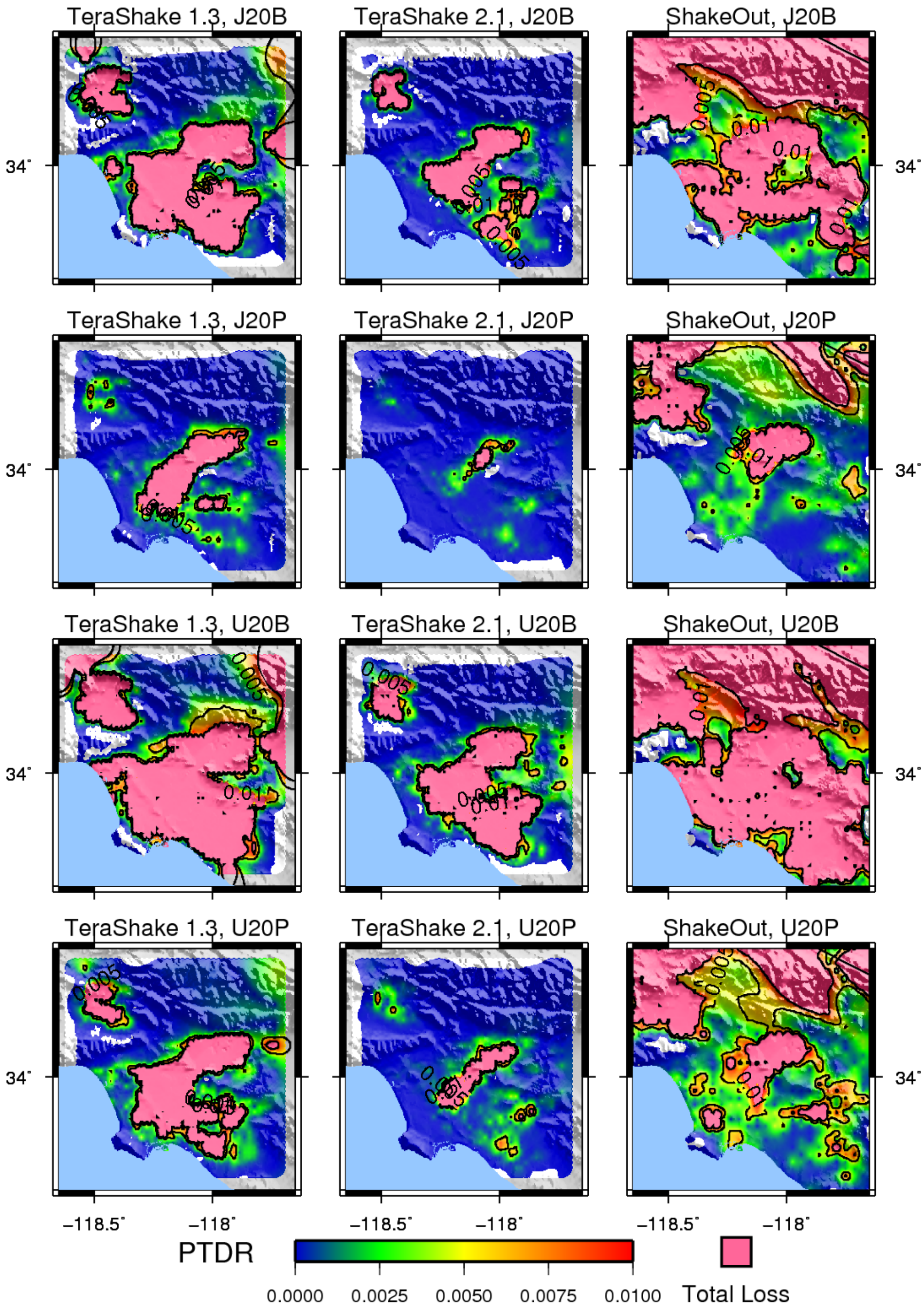

Figure 5.4: This figure shows the permanent total drift ratios for twenty-story buildings in the TeraShake 1.3 (maps on left, kinematic source model), TeraShake 2.1 (maps in middle, dynamic source model), and ShakeOut (maps on right, kinematic source model) simulations. Note the reduction in building response from TeraShake 1.3 to 2.1 due to smaller ground motions from a less coherent source model. Presumably, a dynamic source model of the ShakeOut earthquake would produce smaller ground motions and thus smaller building responses. Nonetheless buildings with brittle welds throughout the Los Angeles and San Fernando basins do not fare well in these great, distant earthquakes.

total structural loss to collapse for buildings with perfect welds. For buildings with brittle welds, an increase in peak ground velocity of less than 0.3 m/s will effect this change in expected building response.

A small margin between total structural loss and collapse is problematic for predicting such important states of building response. As seen in Section 4.4, multiple realizations of the same magnitude earthquake on the same fault result in different predicted peak ground velocities. There is uncertainty in predicting the largest peak ground velocity for a single earthquake, and the uncertainty only increases when trying to establish the seismic risk at a site. If the increment of peak ground velocity from total structural loss to collapse is similar to the uncertainty of predicting the peak ground velocity itself, then distinguishing between total structural loss and collapse is difficult.

5.3 Distant versus Basin Simulations

Although ruptures on the southern San Andreas fault are distant to urban areas, building responses to ground motions from these great earthquakes are comparable to those from large earthquakes in the Los Angeles basin. Figure 5.6 maps the responses of a twenty-story building in three distant, magnitude 7.7 and 7.8 earthquakes and in a Puente Hills earthquake in the Los Angeles basin. The pattern of large building responses is quite different in the four earthquakes. Considering the Puente Hills (top-left subfigure) and the TeraShake 2 (bottom-right subfigure) simulations, the responses of the twenty-story, more flexible building exceed a peak inter-story drift ratio of 0.007 on most of the Los Angeles, San Fernando, and San Gabriel basins. FEMA 356 defines this level as “immediate occupancy;” in either the distant TeraShake or close Puente Hills earthquake, twenty-story, more flexible buildings may not be safe for immediate occupancy throughout the entire Los Angeles area. The Puente Hills earthquake, however, induces collapses on a larger area than does the TeraShake earthquake.

The building responses as functions of peak ground velocity are generally con-

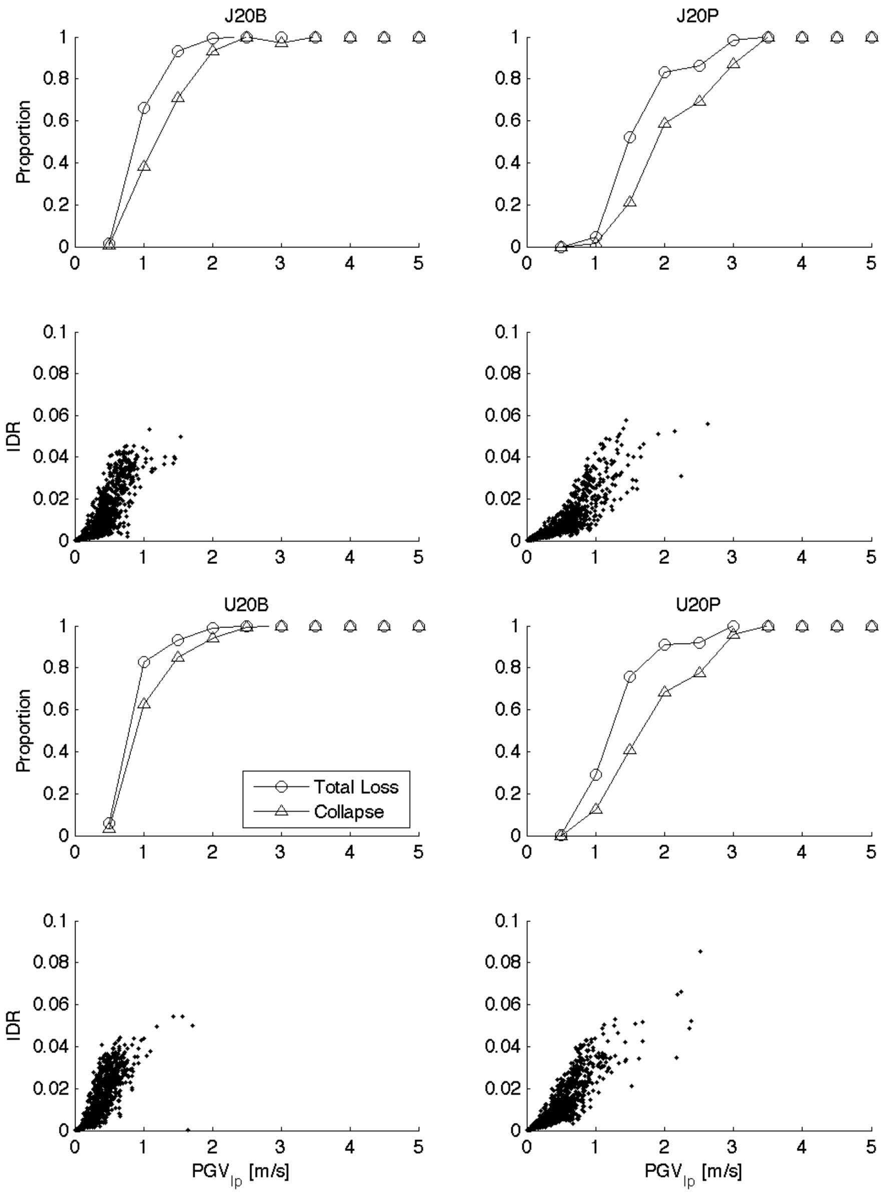

Figure 5.5: This figure shows the twenty-story building responses to magnitude 7.7 and 7.8 simulations on the southern San Andreas fault as functions of the peak ground velocity. The increase in peak ground velocity necessary to change the expected building response from total structural loss to collapse is small. For the buildings with brittle welds, this increase is especially small.

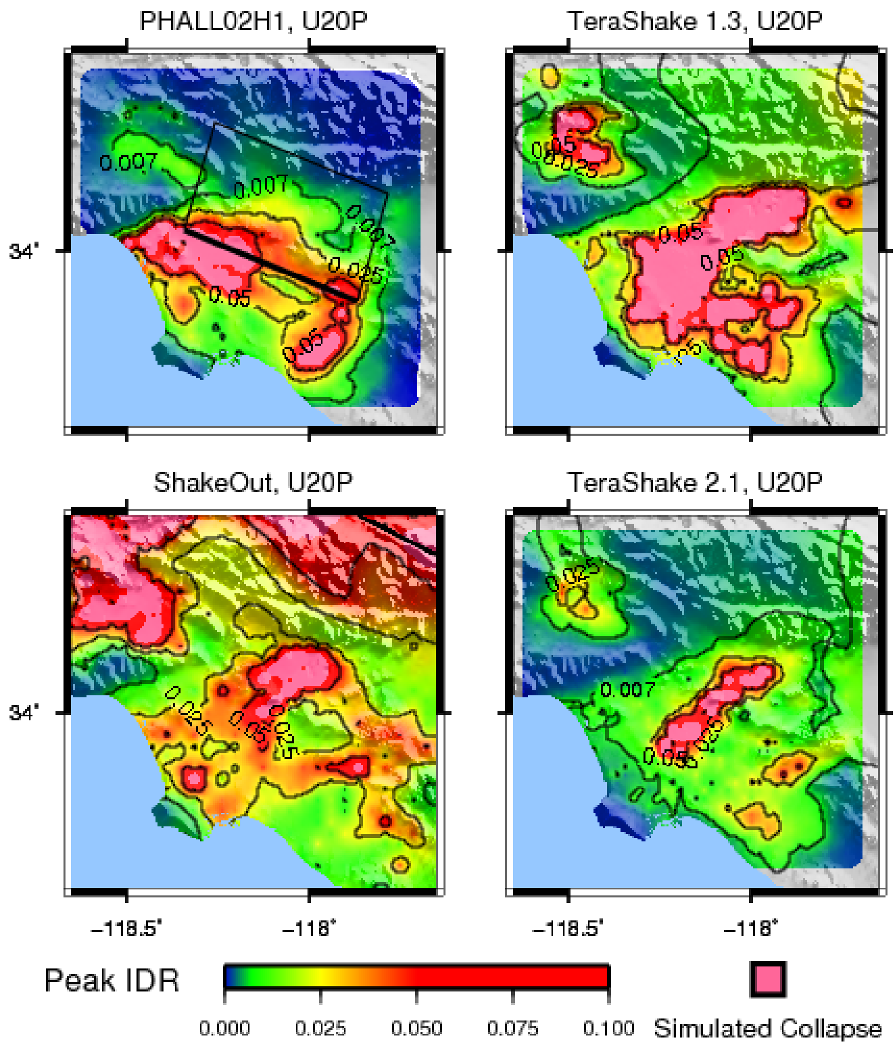

Figure 5.6: These four simulations induce large responses in the twenty-story, more flexible building with perfect welds (U20P). The Puente Hills fault is in the Los Angeles basin, and the TeraShake and ShakeOut simulations rupture the southern San Andreas fault, which is distant from the Los Angeles metropolitan area. The magnitude 7.1 Puente Hills and magnitude 7.7 TeraShake 2.1 simulations suggest that, if either earthquake happened, twenty-story, more flexible buildings throughout the Los Angeles and San Fernando basins may require inspections of the structural systems. (That is, the peak IDR exceeds 0.007, the FEMA 356 immediate occupancy level.) The Puente Hills earthquake induces collapse on a large area compared to the TeraShake 2.1 simulation.

sistent whether the earthquake rupture is distant or near. Figure 5.7 plots the proportions of collapse and total structural loss and the peak inter-story drift ratio versus the ground motion intensity measure. The proportions of collapse from the TeraShake 1 and 2 simulations are larger than those from the ShakeOut and magnitude 7.1 Puente Hills simulations. The differences between TeraShake 2, ShakeOut, and Puente Hills may be due to the normal variation seen previously (for example, Figure 4.13). However, the proportion of collapse from the TeraShake 1 simulation is unusually large. There is a similar difference between the TeraShake versus ShakeOut and Puente Hills simulations as measured by the permanent total drift. For long-period peak ground velocities greater than 1 m/s, the U20P model is always a total structural loss in the TeraShake simulations, but may be repairable in the ShakeOut and Puente Hills simulations. These different building responses may be due to the duration of long-period ground motions in the Los Angeles basin. Considering the building response solely as a function of peak ground velocity neglects this important aspect of ground motion from a distant rupture. Note, though, the consistency in proportion of total structural loss for the four simulations.

The mechanisms of building response are different in near-source ground motions compared to basin-amplified ground motions. In pulse-like, near-source ground motions, the building yields and accumulates damage soon after the transient pulse in ground motion. In the far-source ground motions considered here, sedimentary basins amplify the long-period content and prolong the duration of large ground motion. Thus, the buildings may achieve steady-state resonance, and cyclic excitation may eventually degrade the lateral force-resisting capacity of the buildings. (Section 2.3.1 discusses the different building responses in more detail.) Although the mechanism of building response is different for the two types of ground motions, the end results—measured as collapse, total structural loss, and peak inter-story drift—seem similar for the same peak ground velocity. This observation provides evidence to support using both types of ground motions to develop models to predict building response. In the next chapter, I disregard what simulation produced the ground motions and building responses and consider only the building response as a function of intensity

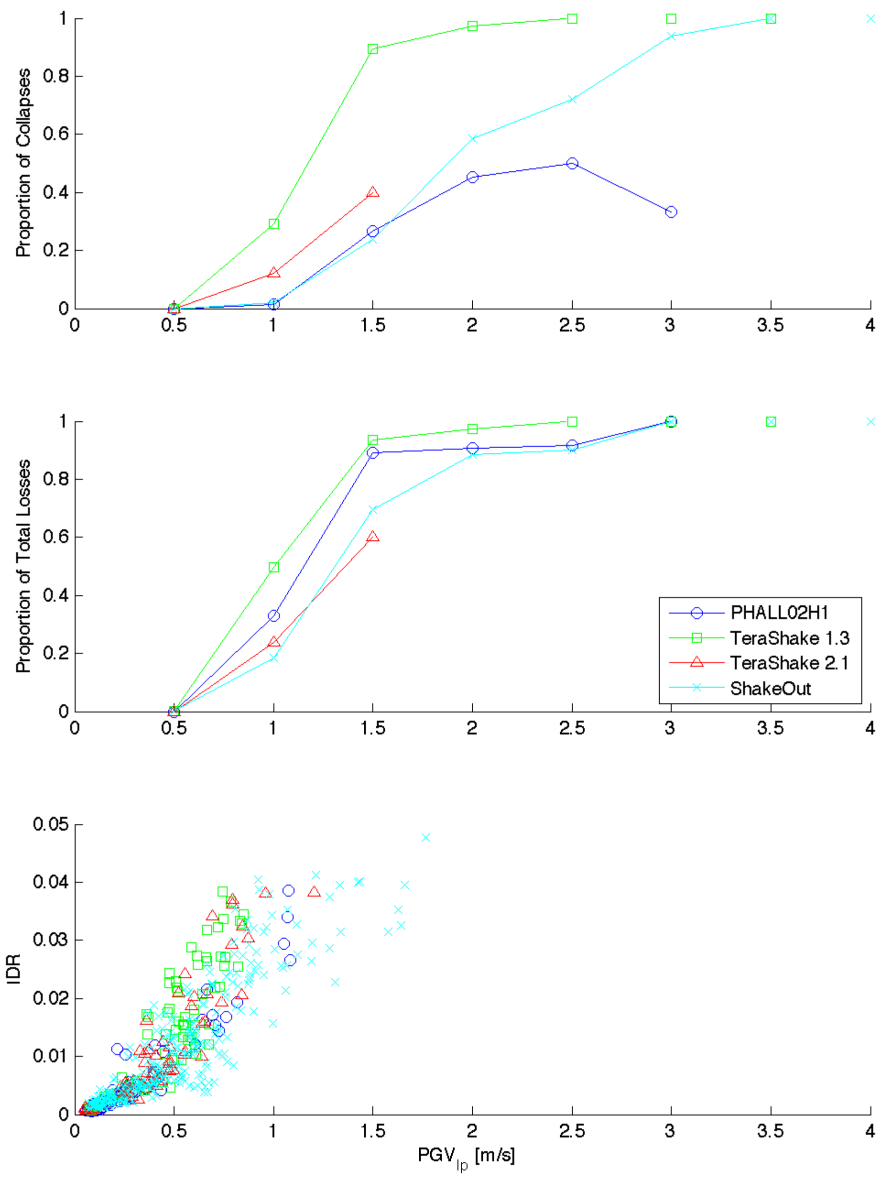

Figure 5.7: The responses of twenty-story, more flexible buildings with perfect welds (U20P) are similar for near-source and basin-amplified ground motions. The TeraShake 1 simulation predicts an unusually large number of collapses for the same peak ground velocity compared to the other simulations. For PGV_{lp} greater than 1 m/s, ground motions from both TeraShake simulations cause the U20P model to be a total structural loss. The differences between building response in the TeraShake versus ShakeOut and Puente Hills simulations may be due to longer duration shaking in TeraShake, which is not characterized by peak ground velocity. Also, the proportion of collapse curve for the Puente Hills simulation (PHALL02H1) is flat and curves down for PGV_{lp} greater than 2 m/s because there is insufficient data from this simulation to characterize collapse at these large values. (Consider Section 4.3.)

measure.