Seismic Intensity Estimation of Tall Buildings in Earthquake Early Warning System

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SUMMARY:
In California, United States, an earthquake early warning system is currently being tested through the California Integrated Seismic Network (CISN) (http://www.cisn.org/eew/CISN_page.html). The system aims to provide warnings in seconds to tens of seconds prior to the occurrence of ground shaking; since the system broadcasts the location and time of the earthquake, user software can estimate the arrival time and intensity of the expected S-wave. However, the shaking experienced by a user in a tall building will be significantly different from that on the ground and this shaking can change significantly from one building to another and also from one floor to another. This paper shows a robust and fast method to predict the characteristics of shaking that can be expected in tall buildings.

Keywords: earthquake early warning system, tall buildings, seismic intensity

1. INTRODUCTION

In California, United States, an earthquake early warning system is currently being tested through the California Integrated Seismic Network (CISN) (http://www.cisn.org/eew/CISN_page.html). The project partners are the California Institute of Technology, the University of California Berkeley, the Eidgenossische Technische Hochschule Zurich (Switzerland), the Southern California Earthquake Center, and the U.S. Geological Survey.

The system aims to provide warnings in seconds to tens of seconds prior to the occurrence of ground shaking, depending on the distance to the epicenter of the earthquake. The estimated location and the magnitude of the earthquake will be updated in real time on a second by second basis. Similar to other earthquake early warning systems, the seismic intensity of the ground motion in a user's location will be provided. However, the shaking level experienced by a user in a tall building will be significantly different from that on the ground. In this paper, an estimation of seismic intensity of tall buildings will be reviewed.

Tall buildings tend to vibrate at their resonant frequencies; these resonant frequencies are typically significantly lower than the frequencies that affect humans at ground level. Furthermore, since the damping of tall buildings is small (less than several percent), the duration of resonant shaking can be large. While it is possible to predict anticipated shaking in a building using a simple ground motion prediction equation (GMPE) that predicts response spectral amplitude from knowledge of earthquake magnitude and epicentral distance, such a prediction may be expected to have very large errors. That is, low-frequency ground motions have more spatial variation than high frequency motions, and these variations are more systematic (e.g., basin motions vs. rock motions). Current state-of-the-art in seismology provides realistic estimates of the time history based on knowledge of the location of an earthquake and a site within a 3-D model of seismic velocities. Strain Green's tensor is used to relate the seismic wave properties between the source location and the user's location. The Green's functions are pre-calculated for different source locations and different users' locations using 3-dimensional seismic velocity model in California. The corresponding building responses at the users' locations are then estimated using finite element and shear beam models. In practice, this information is pre-computed and stored in a database. Once a user provides his street address and which floor he is residing, the seismic intensity of his floor can be quickly provided from the database during an earthquake event. A message, including expected shaking level and shaking duration, will be sent to the users, and such information has shown to be capable of mitigating panic and confusion (Kubo et al, 2011). Different locations, including downtown Los Angeles (a site with many tall buildings), West Pasadena (a hard rock site), and the inter-change between I-90 and I-710 (a Los Angeles basin site), will be used to demonstrate sensitivity of the predicted shaking intensity to the relative geometry of the earthquake/building pair.

2. CISN SHAKEALERT

CISN ShakeAlert is the earthquake early warning system currently being developed in California, which integrates three algorithms in earthquake event detection into a single decision module. The three algorithms include a single-sensor based On-Site method (Böse et al., 2009) and two network-based methods, namely ElarmS (Brown et al., 2011) and Virtual Seismologist (Cua et al., 2009).

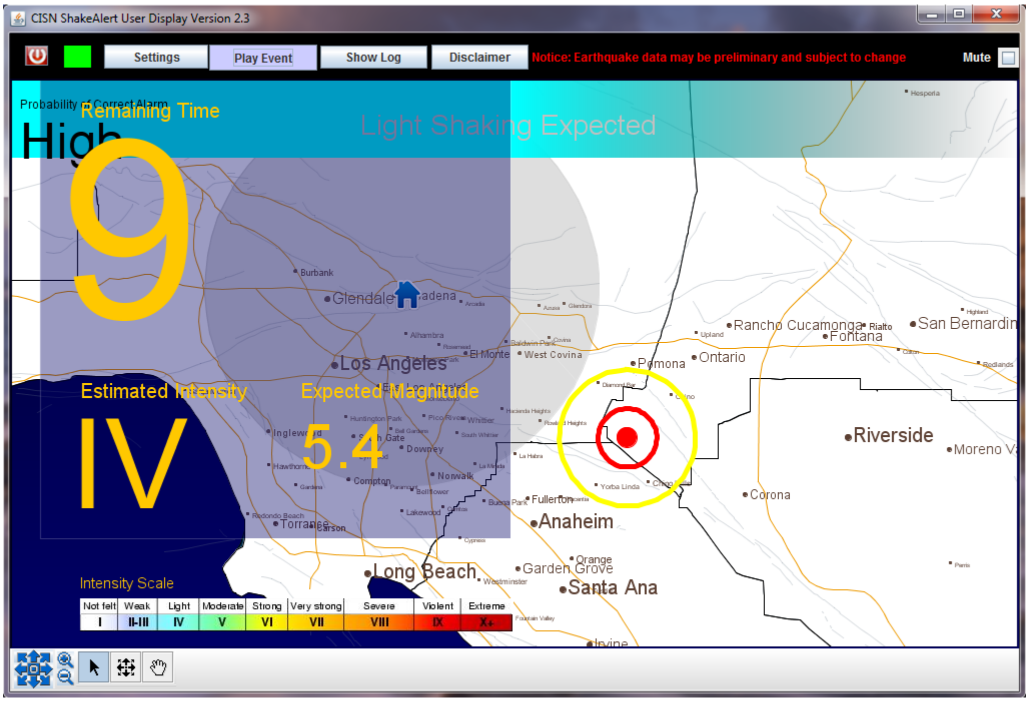


Figure 1. CISN ShakeAlert User Display

CISN ShakeAlert User Display (Böse et al, 2010) receives xml-message from the decision module and display warning information for a given user. The current version is 2.3, and it has the capacity to calculate and display the estimated earthquake magnitude, earthquake epicenter location, remaining warning time, and the expected MMI intensity at the user’s site assuming rock condition (Fig. 1).

3. Ground Motions

In this study, an earthquake is approximately modeled as a point double-couple source. This approximation is inappropriate for ruptures that exceed 20 km in length. Long ruptures are a far more challenging problem that we leave for future work. In this study, we are targeting events in the magnitude M5 to M6 range. There will be tens of these events in the coming decade, and at least some of these events will cause anxiety to occupants of tall buildings. The long-period motions from a point source of any orientation can be obtained from the appropriate linear combination of the strain Green's function (or alternatively, the moment tensor Green's functions).

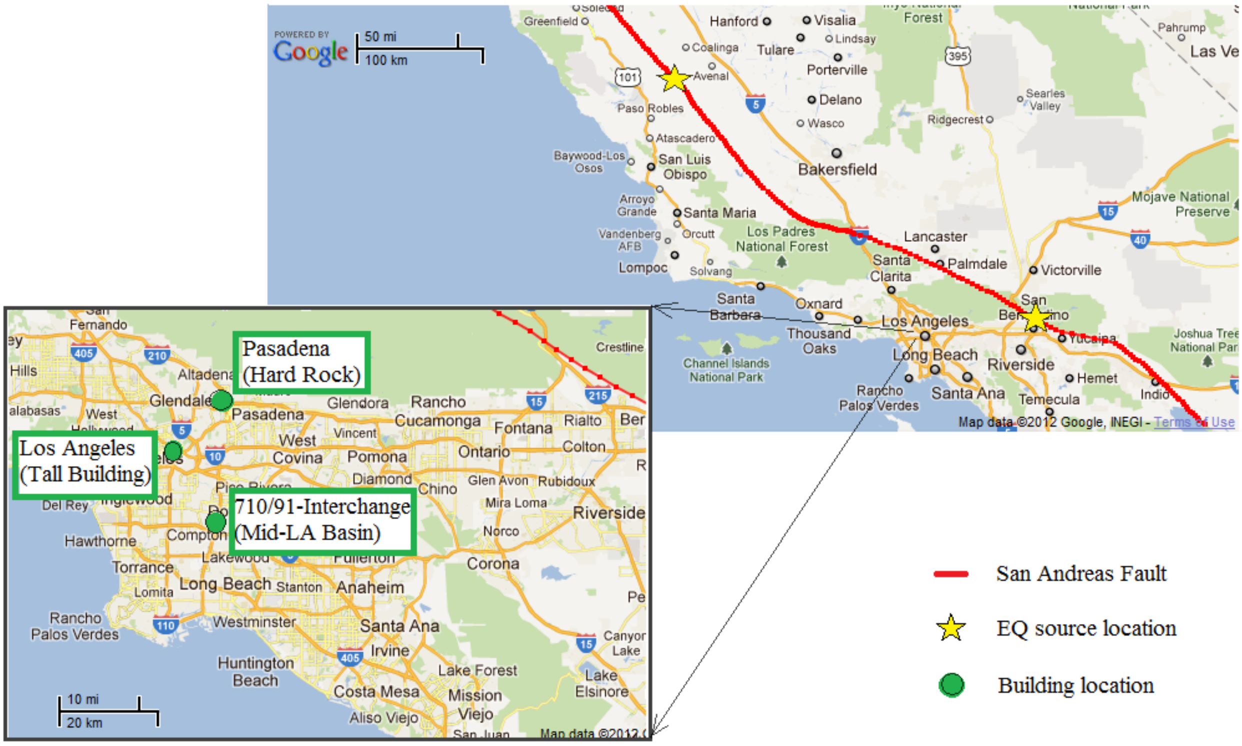


Figure 2. Locations of earthquake sources and buildings

Strain Green's tensors used for the sites of interest in this study are adopted from the Southern California Earthquake Center's (SCEC) CyberShake project (Graves et al., 2010). The 3-D seismic velocity model used in the calculation is the SCEC Community Velocity Model for Southern California (CVM-S) version 4. To demonstrate how an early system for tall buildings might work, we assumed three building locations and we assumed two different M 6 earthquakes on the San Andreas Fault. The assumed earthquake locations are San Bernardino and Parkfield. The assumed building locations are downtown Los Angeles (a site with many tall buildings), West Pasadena (a hard rock site), and the inter-change between I-90 and I-710 (a Los Angeles basin site) (Fig. 2). Distances between the earthquake sources and the building sites are presented in Table 1.

Table 1. Distances between earthquake sources and buildings

		Earthquake source location	
		San Bernardino	Parkfield
Building location	Los Angeles	88 km	285 km
	Pasadena	78 km	284 km
	I-710/91	82 km	300 km

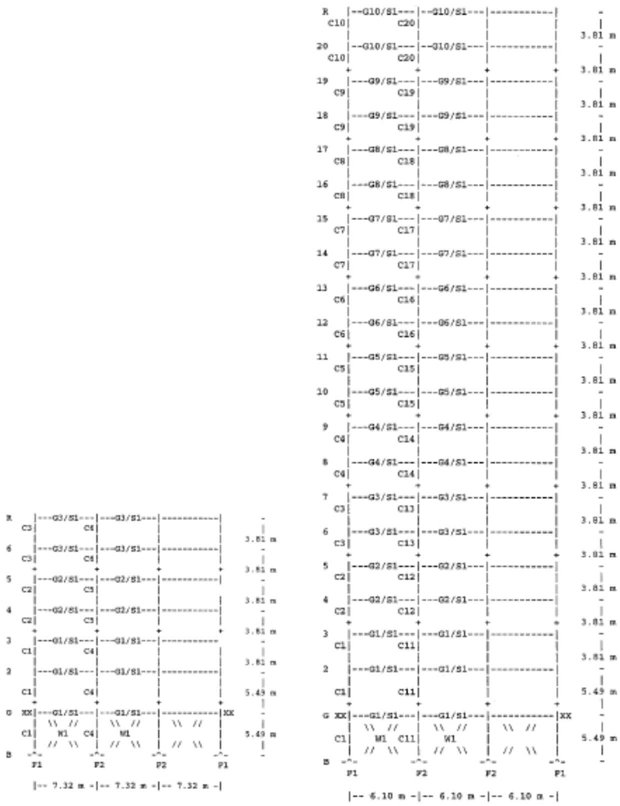
4. SIMULATION OF BUILDING RESPONSES

Two finite element models of steel moment-frame buildings (Fig. 3), one with 6 stories and another with 20 stories, are used to assess the building responses under earthquakes. Both buildings have storey heights of 3.81 m for every storey except the first storey that is assumed to be 5.49 m. Column spacing is 7.32 m for the 6-storey building and 6.1 m for the 20-storey building. The models are designed according to the 1994 Uniform Building Code (Hall 1994). A36 steel is used in the design of both beams and columns. Design dead loads are 3.83 kPa for the roof, 4.55 kPa for the floors, and 1.68

kPa for the cladding. The floor design live load is 2.39 kPa. Gravity load plus wind and gravity loads, as well as seismic loads, are considered in the design. Fundamental natural frequency for the 6-storey building is 0.64 Hz, while that for the 20-storey building is 0.29 Hz. Other natural frequencies of the buildings are presented in Table 2. Other details of the buildings can be found in the report by Hall; 1997.

Table 2. Natural frequencies of the buildings

	6-storey building	20-storey building
1st natural frequency (f_1)	0.64 Hz	0.29 Hz
2nd natural frequency (f_2)	1.81 Hz	0.93 Hz
3rd natural frequency (f_3)	3.01 Hz	1.64 Hz
f_2/f_1	2.83	3.21
f_3/f_1	4.71	5.66



(a) 6-storey building (b) 20-storey building

Figure 3. Finite element models of the 6-storey and 20-storey buildings

Referring to the previous section, CISN ShakeAlert can estimate the earthquake source location and magnitude when an earthquake strikes. However, the seismic waves transmitted to the user's location are different for different focal mechanisms; given the location of the seismic source and the seismic magnitude are the known. For each building site, a total set of 27 wave forms are generated for each earthquake location with the following combinations of parameters: dip of 0°, 45°, and 90°; rake of 0°, 45°, and 90°; and strike of 0°, 45°, and 90°. Earthquake source depth is assumed to be 7 km. Although the local site effect is taken into account in this study by the 3-D seismic velocity model, there is no soil layer in the model. Soil resonance at the period of our buildings is probably not a dominant effect, but it would clearly need to be considered in areas with very soft soils.

Fig. 4 shows the ground motions for different building sites due to a M6 earthquake at San Bernardino with dip= 90°, rake= 180°, and strike = 120°. Although the three building sites are located at similar distance away from the earthquake source, the effect of the Los Angeles basin, which is seen at the I-710/91 causes the remarkably different ground motions than is seen at the two other sites.

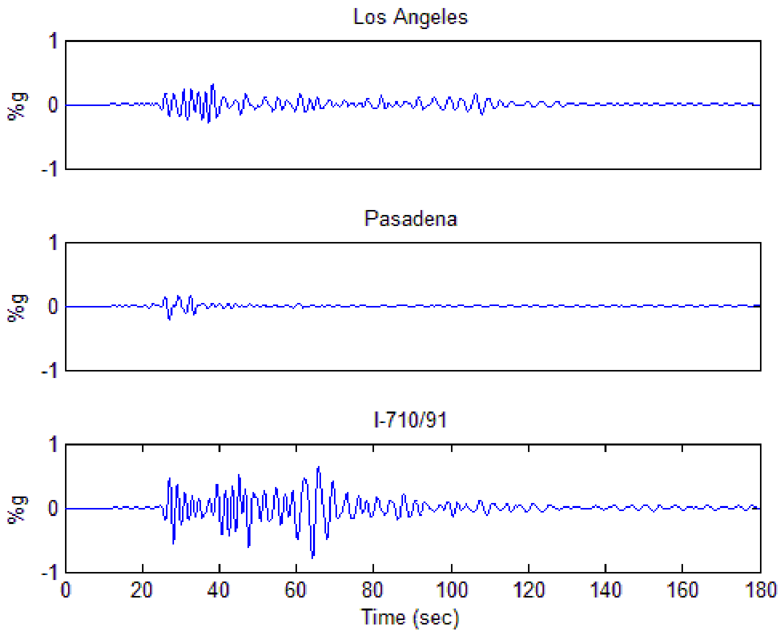


Figure 4. Ground motions for different building sites due to a M6 earthquake at San Bernardino with dip= 90^o, rake= 180^o, and strike = 120^o

Although our finite element simulations includes nonlinear effects, the particular earthquakes that we chose were sufficiently small that all of the simulated motions were within the linear range; that is, traditional modal analysis could have been used to simulate the building motions. Furthermore, the modal properties of these buildings can be obtained from a simple shear beam analysis. For example, the natural frequency ratios (the frequency of the ith mode divided by the frequency of the 1st mode) of the 6-storey building are 1, 2.83, and 4.71; while that of the 20-storey building are 1, 3.21, and 5.66 (Table 2). These ratios are very close to the 1, 3, and 5, ratios that a simple fixed-base shear beam exhibits. Building response using continuous shear beam structure has been well studied in the past (e.g. Iwan,1997; and Sasani et. al, 2006). In our current study, a fixed base shear beam with stepped damping (Roberts and Lutes, 2003) is adopted to simulate the building responses. Damping ratios of 8.5% and 2.5% are selected for the 6-storey building and 20-storey building, respectively. Comparisons of top-floor and mid-floor acceleration responses for the buildings on the I-710/91 site due to a M6 earthquake at San Bernardino with dip= 90^o, rake= 180^o, and strike = 120^o are presented in Fig. 5. It shows that for the purpose of estimating the seismic intensity, the result of a regular steel-frame building designed according to UBC code can be well approximated by a shear beam model in the linear regime.

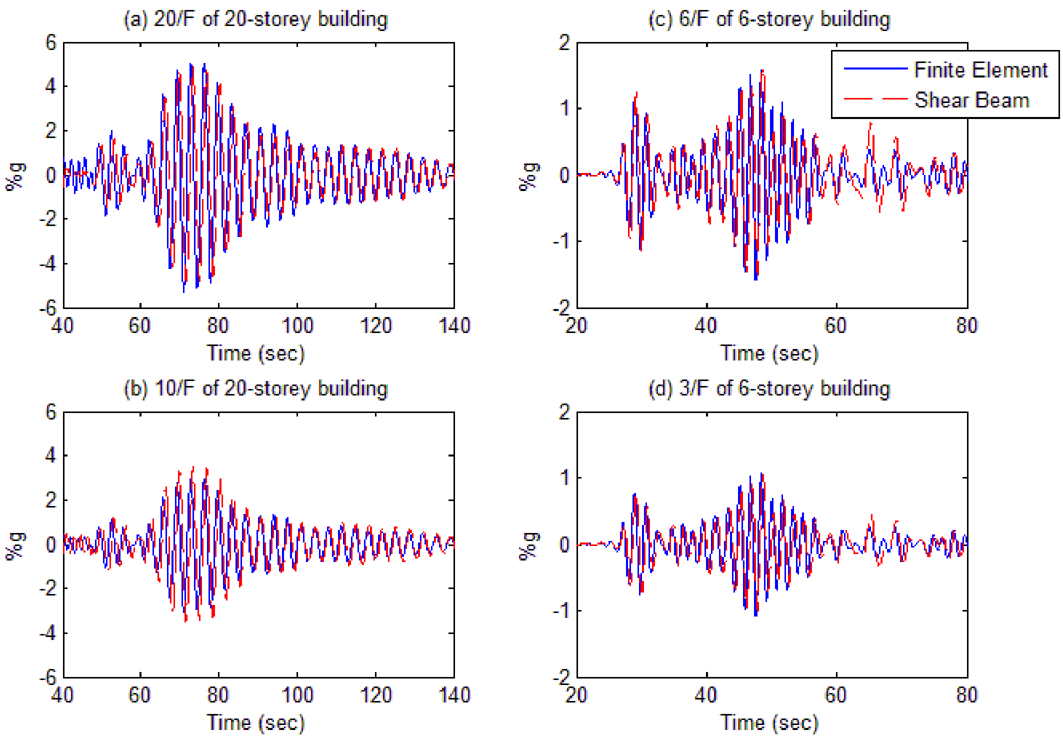


Figure 5. Comparison of responses from finite element models and shear beam models for the buildings in I-710/91 assuming a M 6 in San Bernadino with dip= 90°, rake= 180°, and strike = 120°. (a) Response at 20/F of 20-storey building; (b) Response at 10/F of 20-storey building; (c) Response at 6/F of 6-storey building; (d) Response at 3/F of 6-storey building

While the acceleration response can be derived by the appropriate modal summation, the response of a uniform shear beam is especially simple if it is written as a summation of vertically propagating shear waves that reflect at the top and the bottom of the building. The acceleration response solution for a fixed-base shear beam with stepped damping is described as follows:

$$\ddot{u}(x,t) = \sum_{k=0}^{\infty}(-1)^k\, e^{-k\pi\xi}\, \ddot{u}_g\left(t - \frac{x}{4Hf} - \frac{k}{2f}\right) - \sum_{k=1}^{\infty}(-1)^k\, e^{-k\pi\xi}\, \ddot{u}_g\left(t - \frac{x}{4Hf} + \frac{k}{2f}\right) \quad (4.1)$$

where $\ddot{u}(x,t)$ is the acceleration response; x is the vertical distance from the ground; H is the height of the building; ξ is the damping ratio; $\ddot{u}_g(t)$ is the ground acceleration motion; f is the fundamental natural frequency of the building.

5. HUMAN RESPONSE TO SEISMIC INTENSITY

Human's perception of shaking is a complex subject that involves different psychological factors. Researchers suggest that people are in general insensitive to velocity if visual effects are not considered. It is because no force is required by the body to counter-balance any motions in constant velocity. Instead, a person feels constant force is acting on him when he experiences a constant acceleration. A continuous adjustment of the body is necessary for a human to adapt to a varying force with changing acceleration during earthquakes. The subject of human comfort threshold in tall buildings has been widely studied in the past (e.g. Bashor et al., 2005; and Boggs, 1995). The relation between human comfort level and peak acceleration is shown in Table 3 (Griffis, 1993).

Table 3. Human comfort level to acceleration

Peak Acceleration	Comfort level	Early warning message
< 0.5% g	Not perceptible	No shaking
0.5% - 1.5% g	Threshold of perceptible	Minor shaking
1.5% - 5% g	Annoying	Moderate shaking
5% - 15% g	Very Annoying	Strong shaking

Current earthquake early warning systems in the US (currently just a demonstration system) and Japan provide the estimated seismic intensity at the ground level of a given site during earthquakes. However, the acceleration level, as well as human comfort, is totally different in a tall building than on the ground. During the M9 Tohoku earthquake in Japan on 2011, roof accelerations on some tall buildings in the Tokyo metropolitan area were amplified by a factor of 3.5 comparing to the ground motions (Kasai et al., 2012). Some real-time structural monitoring systems are installed in US (e.g. Bradford et al., 2004) and Japan (e.g. Kasai et al., 2012), in which they provide the acceleration waveform, maximum acceleration, velocity, and displacement in real time. Such data can be used to interpret the seismic intensity level, as well as the level of indoor damage. However, the users will have no time to react to such information in real time.

In practice, the acceleration responses of a building can be pre-computed and stored in a database. Google Earth can be used to retrieve the dimensions of buildings at a street address. Natural frequencies of the building can either be estimated, or they can be measured from ambient vibration data recorded on newly developing volunteer seismic networks (e.g., the Community Seismic Network (Clayton et al, 2011), or the Quake Catchers Network (Cochran et al., 2009)).Once a user provides his street address and the floor on which he is residing, the seismic intensity of his floor can be quickly provided from the database during an earthquake event. A message, including expected shaking level (Table 3) and shaking duration, will be sent to the users, and such information has shown to be capable of mitigating panic and confusion (Kubo et al, 2011).

In this study, 27 simulations are generated for each floor of a building for each earthquake source location. As a demonstration of the proposed methodology, an equally weighted mean is taken for the responses on each floor to get the average floor acceleration response on a building. In the future, more weights can be put on those directions of a point source with high probability of rupture. For the sake of estimating human discomfort and anxiety, the direction of acceleration does not matter, so the envelope of the average floor acceleration responses are used to determine the seismic shaking levels (Fig. 6 and 7). Peak acceleration on the record on each floor is compared to the level of human comfort given in Table 3; appropriate early warning message will be sent out to the user. For example; “this is an earthquake and the building will sway for the next 60 seconds”.

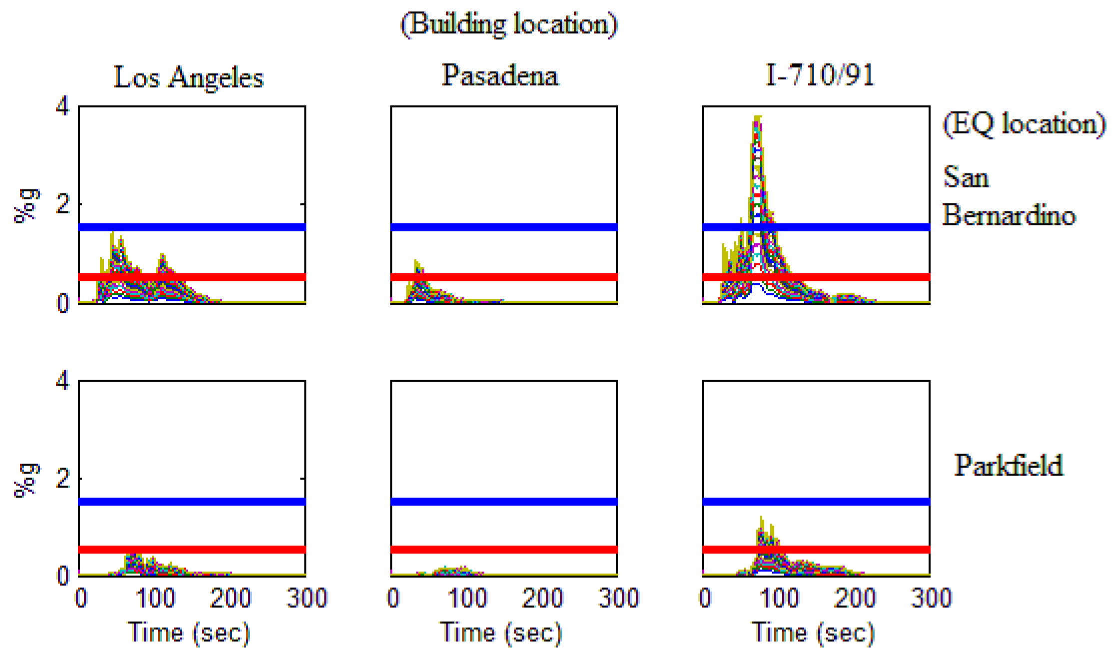


Figure 6. Seismic shaking level for 20-storey building. 20 curves on each plot correspond to different floor acceleration responses. (Red line: threshold for minor shaking; Blue line: threshold for moderate shaking)

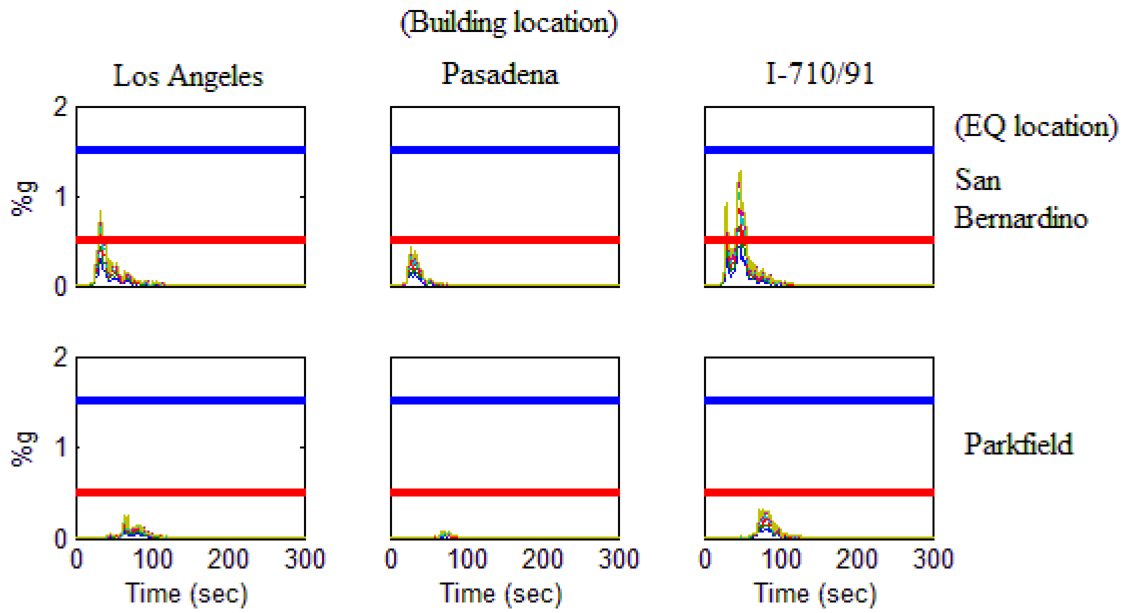


Figure 7. Seismic shaking level for 6-storey building. 6 curves on each plot correspond to different floor acceleration responses. (Red line: threshold for minor shaking; Blue line: threshold for moderate shaking)

The time length for which the acceleration record is higher than the threshold for shaking perception (0.5% g) is taken as the expected shaking duration. For example, if a person is residing at the 10th floor of a 20-storey building at I-710/91, he will receive the following sample early warning message when an earthquake in San Bernardino strikes: "Moderate shaking coming in x seconds. Please remain calm and stay away from the windows. The building will continue to sway for approximately 100 seconds" (Note: the x seconds are provided by the CISN ShakeAlert decision module as discussed in Section 2, and this time value will be updated and counting down in the User Display).

6. FUTURE WORK

1. Model all the possible building sites and earthquake source locations in California.
2. Simulate magnitude M7 or higher earthquakes by finite-fault sources.
3. Simulate non-linear behaviors of buildings and the expected shaking levels in strong earthquakes.

7. CONCLUSION

An estimation of seismic intensity of tall buildings has been demonstrated in this paper. Different locations, including downtown Los Angeles (a site with many tall buildings), West Pasadena (a hard rock site), and the inter-change between I-90 and I-710 (a Los Angeles basin site), has been used to review the sensitivity of the predicted shaking intensity to the relative geometry of the earthquake/building pair. Furthermore, the estimations of building responses at the users' locations using finite element models have been compared to those using shear beam models.

AKCNOWLEDGEMENT
This work is partially supported by National Science Foundation (EAR-1027790), George Housner Earthquake Engineering Research Endowment (EAS-41212), Fred L. Hartley Family Foundation, and Croucher Foundation. Their support is gratefully acknowledged.

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