Seismic Hazard Mapping of California Incorporating Spatial Variability of Site Conditions

by

Erol Kalkan[1], Chris J. Wills[2], and David M. Branum[3]

ABSTRACT

The U.S. Geological Survey has recently released a 2008 version of the probabilistic National Seismic Hazard Maps. These maps plot the peak ground acceleration (PGA) and spectral acceleration (SA) ordinates at 0.2 and 1.0 sec with 2% and 10% probabilities of being exceeded in 50 years, corresponding to earthquake return periods of about 2,475 and 475 years, respectively. These acceleration levels were computed for uniform "firm rock" site conditions, i.e., 760 m/sec average shear-wave velocity in the upper 30 m, and therefore these maps do not show the potential spatial variability of ground motion associated with different site conditions, so we have combined the USGS National Seismic Hazard model with the California showing 17 generalized geologic units geologic units that can be defined by their shear-wave velocity (Wills and Clahan 2006), we regrouped these units into to 7 shear-wave velocities. At each shear-wave velocity value, a probabilistic seismic hazard map was generated for the entire state. By combining seismic hazard maps based on the 7 different shear-wave velocity values, a suite of seismic hazard maps was computed for California for 0.2 and 1.0 sec spectral ordinates at 2% probability of being exceeded in 50 years. The improved maps thus explicitly incorporate the site effects and their spatial variability on ground motion estimates. The SA at 1.0 sec map of seismic shaking potential for California has been now published as California Geological Survey Map Sheet 48, which is intended to be accessible and understandable to the general public.

INTRODUCTION

The National Seismic Hazard Maps (Petersen et al 2008) are the standard depiction of seismic hazard across the United States. These maps are aimed to identify the possible seismic demands not only for design of new and rehabilitation of existing structures, but also for emergency planning, loss estimation and risk assessment. These maps use a uniform set of input parameters and calculations that are developed though numerous workshops and conferences with the participation of seismologists, geologists, and engineers. In California the 2008 National Seismic Hazard Maps are based on a seismic hazard model, the Uniform California Earthquake Rupture Forecast developed by the Working Group on California Earthquake Probabilities (WGCEP 2008) through a similar open, inclusive process. The National Seismic Hazard Maps show the level of ground motion with a 2% probability of being exceeded in 50 years, a value chosen for structural design applications in building codes. These maps show the spatial variability of seismic hazard considering the potential earthquakes on faults with known slip-rates and also background seismicity.

For the National Seismic Hazard Mapping Program (NSHMP), ground motion is calculated for the maps assuming that all sites are "firm rock", that the site conditions can be described by an average shear-wave velocity (V_{S30}) in the upper 30 meters as 760 m/sec. In depicting the variability of earthquake hazard across a region, assuming a uniform "firm rock" condition across the area results in a pattern of ground motion that falls off smoothly from the major faults, and misses the areas of high potential ground shaking due to amplification of seismic waves by the near surface soils which is commonly referred to as site-amplification. During the 1985 Mexico City (Mexico), and 1989 Loma Prieta (California) earthquakes, amplification due to near surface soils resulted in significant damage to structures (Anderson et al. 1986, Holzer 1994). As a result, current building codes in U.S. (e.g., CBC2007, IBC2006) require consideration of site-amplification when estimating the seismic demand on a structure by modifying the "firm rock" ground motion by a set of factors determined for

[1] Erol Kalkan, United States Geological Survey, MS977, 345 Middlefield Rd., Menlo Park, California 94025, ekalkan@usgs.gov
[2] Chris J. Wills, California Geological Survey, 801 K St. MS 12-32, Sacramento, California 95814, Chris.Wills@conservation.ca.gov
[3] Dave M. Branum, California Geological Survey, 801 K St. MS 12-32, Sacramento, California 95814, Dave.M.Branum@conservation.ca.gov

representing generic site classifications (Borcherdt 2002). Recognition of the importance of site amplification has also prompted efforts to map site conditions at regional and state-wide scales. For example, Seekins et al. (2000) studied soil type and associated shaking hazard in the San Francisco Bay area, while Wills et al. (2000) and later Wills and Clahan (2006) mapped the geographic distribution of V_{S30} for the entire state of California.

For the maps described in this article, we have incorporated the potential amplification by the near surface soils to develop a more complete depiction of potential seismic shaking hazards throughout California. Seismic hazard maps incorporating the site effects were computed for 0.2 and 1.0 sec spectral ordinates at 2% probability of being exceeded in 50 years. The 0.2 and 1.0 sec periods are selected because they are frequently used as corner spectral periods to construct a smooth design spectrum for structural design; an appropriate procedure to obtain a smooth design spectrum from a uniform hazard spectrum is given in the FEMA-356 guidelines (ASCE 2000).

The methodology used here to prepare the resulting hazard maps is similar to one used for development of the national seismic hazard maps except it incorporates the impact of shallow geologic units. Comparison of the new hazard maps with the maps prepared by the NSHMP based on uniform rock assumption indicates that incorporating site effects may escalate the ground shaking potential more than two times especially in areas designated with low V_{S30}.

The new hazard maps presented in this article are useful for both code applications and input to earthquake loss models. The SA at 1.0 sec map of seismic shaking potential for California has been published now as California Geological Survey Map Sheet 48, which is intended to be accessible and understandable to the general public.

DEVELOPING THE EARTHQUAKE SHAKING POTENTIAL MAP FOR CALIFORNIA

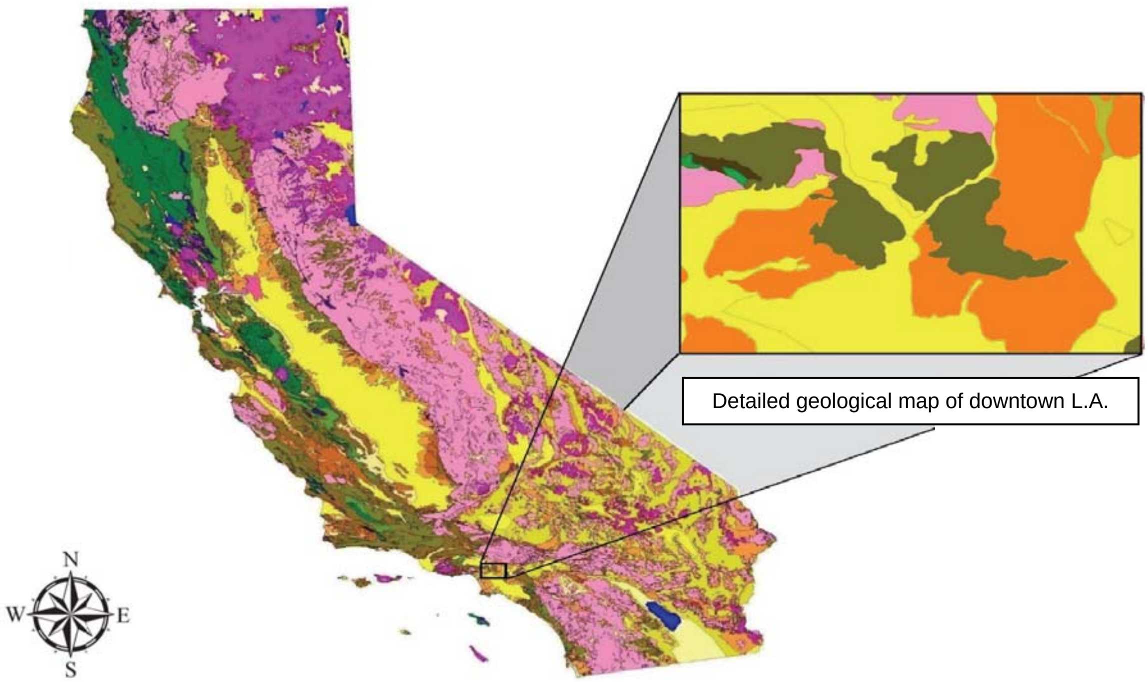
To show the potential for earthquake shaking, we applied the seismic hazard computer code developed for the National Seismic Hazard Maps. This code incorporates the Uniform California Earthquake Rupture Forecast and the Next Generation of Attenuation (NGA) relations for calculating ground shaking in a complete, consistent format where each aspect of the calculation has been extensively reviewed. For hazard computations in California, we have considered the hazard contributions due to the active faults in California, adjacent parts of Nevada and Oregon, and the Cascadia Subduction zone.

The NSHMP code calculates a grid of ground motion values with a specified probability at a chosen spectral period. Although the NSHMP code calculates the ground shaking hazard for a “firm rock” site condition, it can be modified to calculate hazard for any value of V_{S30}.

Wills and Clahan (2006) used the shear-wave velocity characteristics of geologic units updated from those described by Wills and Silva (1998) and applied them to a map that covers all of the sites where shear-wave velocity has been measured. In doing this, they created a new site-conditions map for California where each site can be classified by a general geologic category (see Fig. 1). Several V_{S30} values of the geologically-defined categories were very similar to others. To simplify calculations and production of the state-wide hazard map, the most similar geologic categories could be combined and a composite V_{S30} value used for the combination. By reassembling geologic categories, we were able to simplify the map of Wills and Clahan (2006) from 17 geologic categories into 7 V_{S30} “map groups”. The table embedded in Figure 1 shows the simplified geologic units with calculated mean V_{S30} for that unit from Wills and Clahan (2006); further generalized groups used for calculation of the map grids here are described at the last column.

We used the NSHMP computer code to calculate the seismic hazard with a 2% chance of being exceeded in 50 years for 0.2 and 1.0sec spectral periods for each of the 7 V_{S30} values separately. The resulting grids show the seismic shaking hazard for the specified period (0.2 or 1.0sec) and V_{S30} (160, 216, 287, 377, 489, 609 or 760 m/sec). In the next step, we contoured each of the seven maps of gridded values for each period in GIS environment to create polygons with a discrete range of values. The final map for each period was created by cutting the polygons defined from the grids using polygons from the V_{S30} map, then assembling the final map using the polygons defined based on the grid for a specific V_{S30} in place of the whole V_{S30} polygon. A schematic procedure for generating state-wide hazard map incorporating spatial variability of soil is shown in Figure 2. Another approach to incorporate soil effects onto hazard map would be assigning a V_{S30} value corresponding to each grid point using the geology map as a reference, and conduct a single probabilistic seismic hazard analysis based on a varying V_{S30} values on the grid. Although, this approach seems to be computationally attractive, the resultant hazard values would mask the local peaks and valleys due to smoothing process between grid points (initially spaced at .05°). It should be noted that the digitized boundaries are more precisely located than the grid; therefore the boundaries are shown more clearly using the polygons with different V_{S30} than using the grid (which has a resolution of .05°).

In computing the seismic hazard for California, only three NGA relations were used (Campbell and Bozorgnia 2008; Boore and Atkinson 2008; Chiou and Youngs 2008). The Campbell and Bozorgnia and Chiou and Youngs relations require the basin depth as an input parameter. Currently, there is no statewide basin depth map available yet to account for spatial variability of this value; therefore, a fixed value of 2.0 km was utilized using the two NGA relations. 2.0 km is selected because it averages the basin-depth effect on ground motion predictions (S. Harmsen, personal comm.).



Geologic Unit	Geologic Description	Unit V_{S30} (m/sec)	Map Group V_{S30} (m/sec)
Qi	Intertidal Mud including “bay mud”	160	160
Qal, deep, Imperial V	Holocene alluvium in the Imperial Valley.	209	216
aft/qi	Artificial fill over intertidal mud around San Francisco Bay.	217	
Qal, fine	Fine grained Quaternary (Holocene) alluvium.	236	
Qal, deep	Quaternary (Holocene) alluvium in deep basins.	280	287
Qal, deep, LA Basin	Quaternary Holocene alluvium in the Los Angeles basin.	281	
Qs	Quaternary (Pleistocene) sand deposits.	302	
Qal, coarse	Coarse grained Quaternary (Holocene) alluvium	354	377
Qal, thin	Thin (Holocene) alluvium underlain by contrasting material within 30m.	349	
Qoa	Quaternary (Pleistocene) alluvium	387	
QT	Quaternary to Tertiary (Pleistocene - Pliocene) alluvial deposits.	455	489
Kss	Cretaceous sandstone.	566	
Tss	Tertiary sandstone.	515	
Tv	Tertiary volcanic rocks.	609	609
serpentine	Serpentine.	653	
KJf	Franciscan complex rock.	782	760
xtaline	Crystalline; including granitic and metamorphic rocks.	748	

Figure 1. The state-wide map of Wills and Clahan (2006) (figure above) shows 17 geologically defined shear-wave velocity categories with the V_{S30} values in the table. Right columns of the table shows simplified geologic units with calculated mean V_{S30} for that unit, and further generalized for calculation of the map grids described here. A snapshot to LA downtown area indicates the geological detailing of the map.

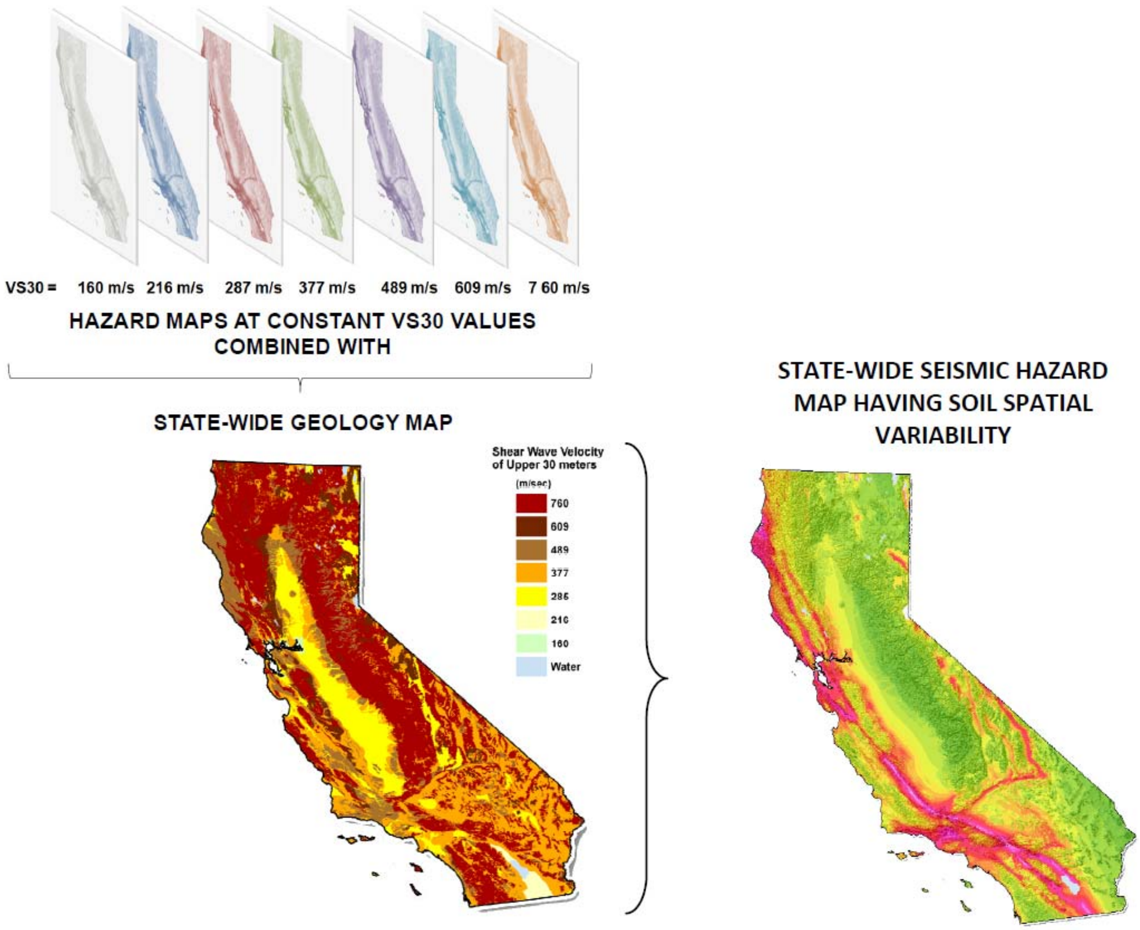


Figure 2. Schematic procedure for generating seismic hazard map for California incorporating soil spatial variability.

SEISMIC SHAKING HAZARD MAPS

Figures 3 and 4 show the mean values of seismic hazard computed from probabilistic seismic hazard analysis for spectral acceleration (SA) at 0.2 and 1.0 sec for 2% in 50 year probability. The distribution of calculated spectral acceleration, shown by the color gradient, indicates higher acceleration values along the active fault lines. Peak values of spectral acceleration reaches at 4.5g at 0.2 sec, and 2.5g at 1.0 sec. The simple pattern of increased shaking hazard near the major seismic sources is clearer in the map of 0.2 sec (Fig. 3), because the surface soils have less effect on the short period shaking. The 1.0 sec period shaking shows much more influence of surface soils. The resulting map shows areas where high shaking hazard extends farther from a fault on one side than the other, because of the increased shaking potential due to soft soils that are only found on one side of the fault lines (this effect is clear along the Hayward fault in the East Bay area as well as others in the basin and range province of eastern California). The map also shows a few areas, for instance the Sacramento-San Joaquin delta, where the soft near-surface soils increase the shaking hazard to levels comparable with areas with more frequent earthquakes.

To demonstrate the influence of soil amplification on the hazard results (i.e., spectral acceleration at 1.0 sec) for the San Francisco Bay area, Figure 5 compares the mean hazard values along the Hayward and northern branch of the San Andreas faults based on a fixed V_{S30} (uniform rock) with hazard values considering spatially variable V_{S30}. The ratio of the hazard values on the two maps in Figure 6 is the amount that the shaking hazard is amplified by the near surface soils. From the map of this ratio, it becomes evident that there are extensive areas of Marin County and smaller areas on the San Francisco Peninsula where the near surface soils do not significantly amplify the potential ground shaking (the ratio is near 1 because the near surface material is “firm rock”). In most of the East Bay, however, there is significant site-amplification. Amplification increases the shaking potential by 25% or more in much of the East Bay hills, because they are underlain by sandstone and shale with V_{S30} values lower than the 760 m/sec of “firm rock”. Amplification is greater in alluvial valleys and in bay muds. In alluvium, soil amplification results in shaking potential ranging from 50% higher to nearly double the “firm rock” level. The bay mud and similar intertidal mud in the delta area more than double the potential shaking hazards from the values calculated for “firm rock”; this level of amplification may be an issue for vulnerability of levee system. The pattern is also complicated by the fact that the NGA relations utilize nonlinear-soil correction (i.e., site amplification decreases with increasing ground-motion intensity as surface materials reach their limit strength and start behaving nonlinearly). This decreases the amplification due to soft-soil deposits along the fault lines (in the near-field zone) to less than 2.0 and close to 1.0 in many locations.

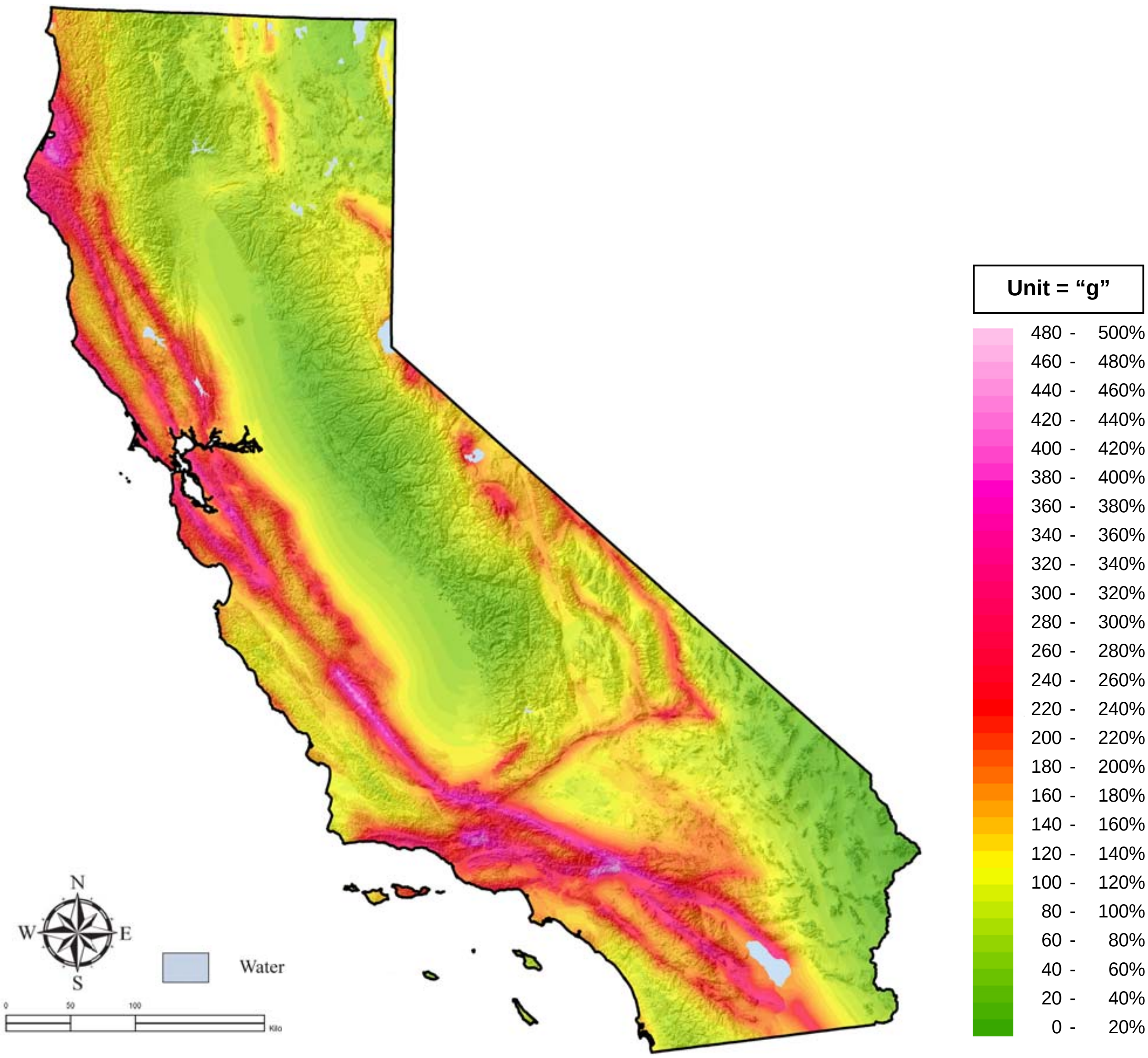


Figure 3. Spectral acceleration at 0.2 sec map for California for 2% probability of exceedance in 50 years.

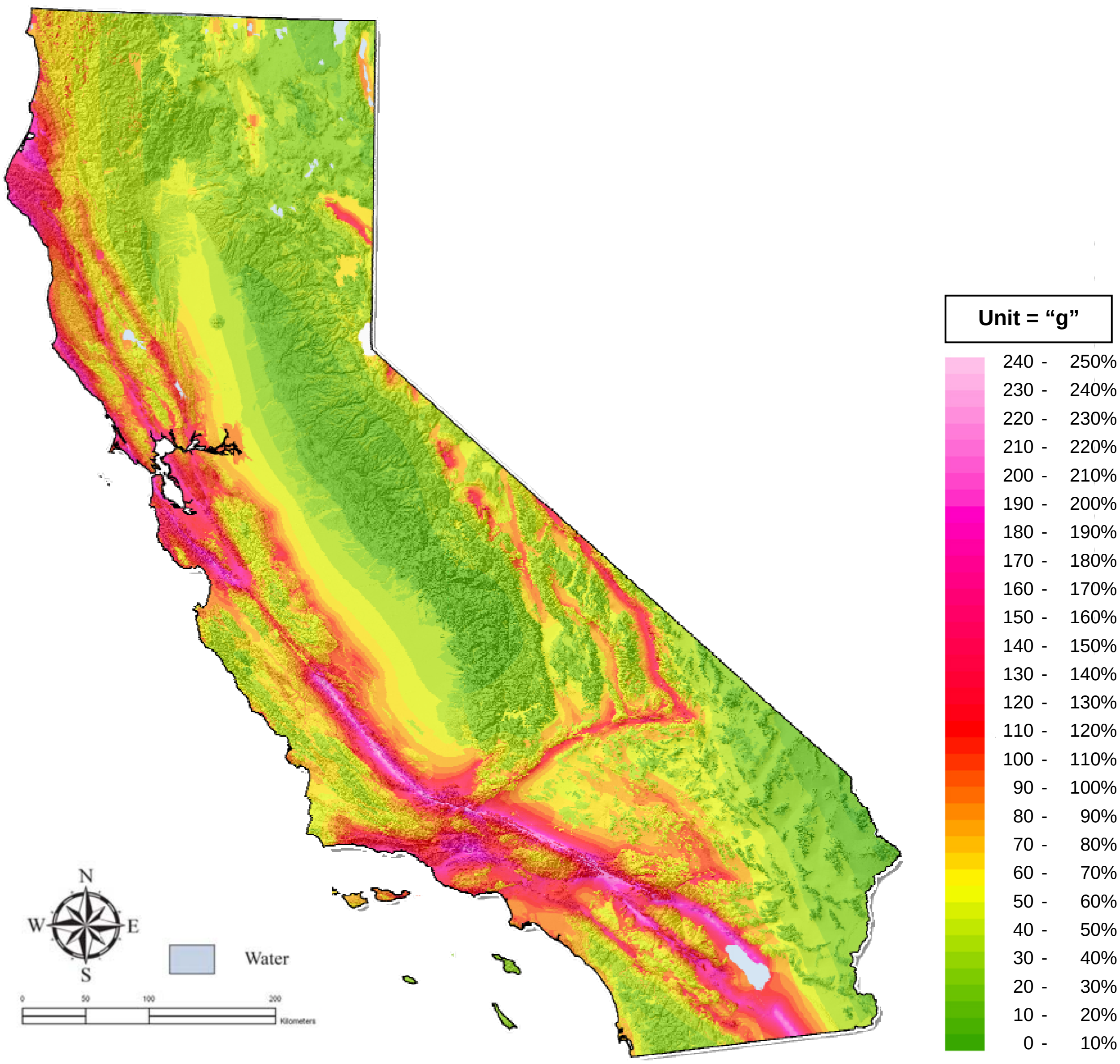


Figure 4. Spectral acceleration at 1.0 sec map for California for 2% probability of exceedance in 50 years.

DISCUSSION

This article describes the geographic distribution of V_{S30} in California, and the potential for site conditions to locally amplify ground shaking hazard. This map differs from the maps prepared by the NSHMP only by its inclusion of amplification of seismic waves by the near-surface soils. Around the bay area, site-amplification alone increases the seismic shaking potential by more than a factor of 2 in areas underlain by bay mud and by factors of more than 1.5 in areas underlain by Holocene alluvium.

The new hazard maps presented in this article are useful for both code applications as reference for site-specific hazard analysis (not intended to replace site-specific hazard analysis) and input to earthquake loss models. The SA at 1.0 sec map of seismic shaking potential for California (Fig. 4) has been now published as California Geological Survey Map Sheet 48, which is intended to be accessible and understandable to the general public. That published map includes maps of the source data for the seismic hazard model, historic earthquakes and fault slip rates. It also includes maps described here: the seven V_{S30} categories, and 0.2 and 1.0 second SA shaking potential. These are described on the map as "high frequency" and "low frequency" seismic shaking. Spectral values at 0.2 and 1.0 sec mapped because these are two corner periods used to construct the smooth design spectrum for the building code and to calculate earthquake losses. As noted on the map, high frequency shaking has greater effects on short or stiff structures, while low frequency shaking has more effect on tall or flexible structures. The map also explains that site conditions have a greater effect on the low frequency seismic hazards, and that the low frequency hazard map is probably the best single depiction of the overall hazard.

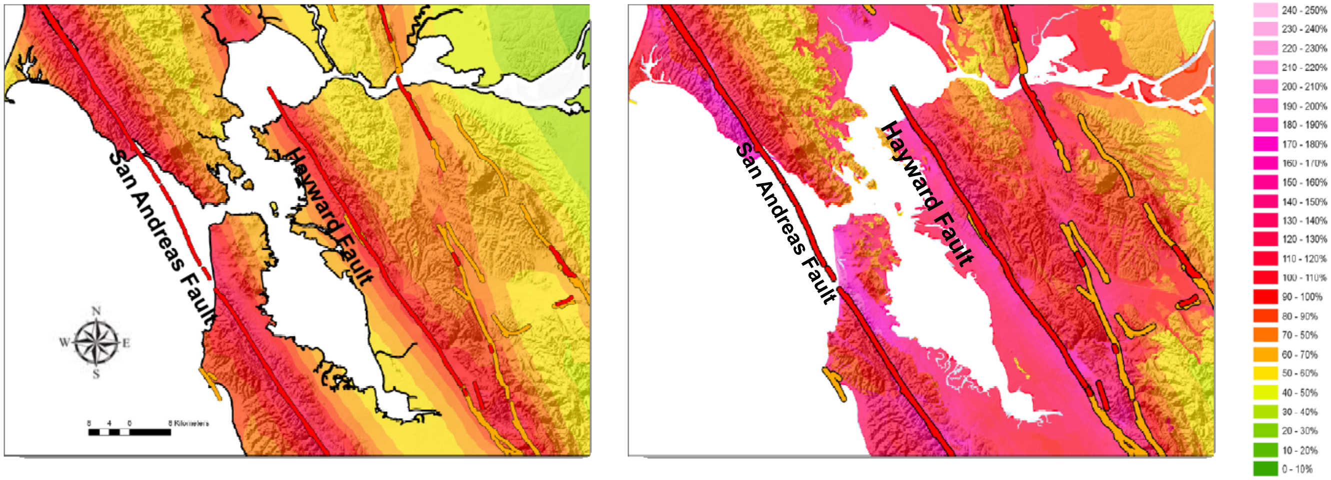


Figure 5. Close up view to seismic hazard along the Hayward and northern branch of San Andreas faults; maps show SA at 1.0 sec with 2% probability of exceedance; unit = "g".

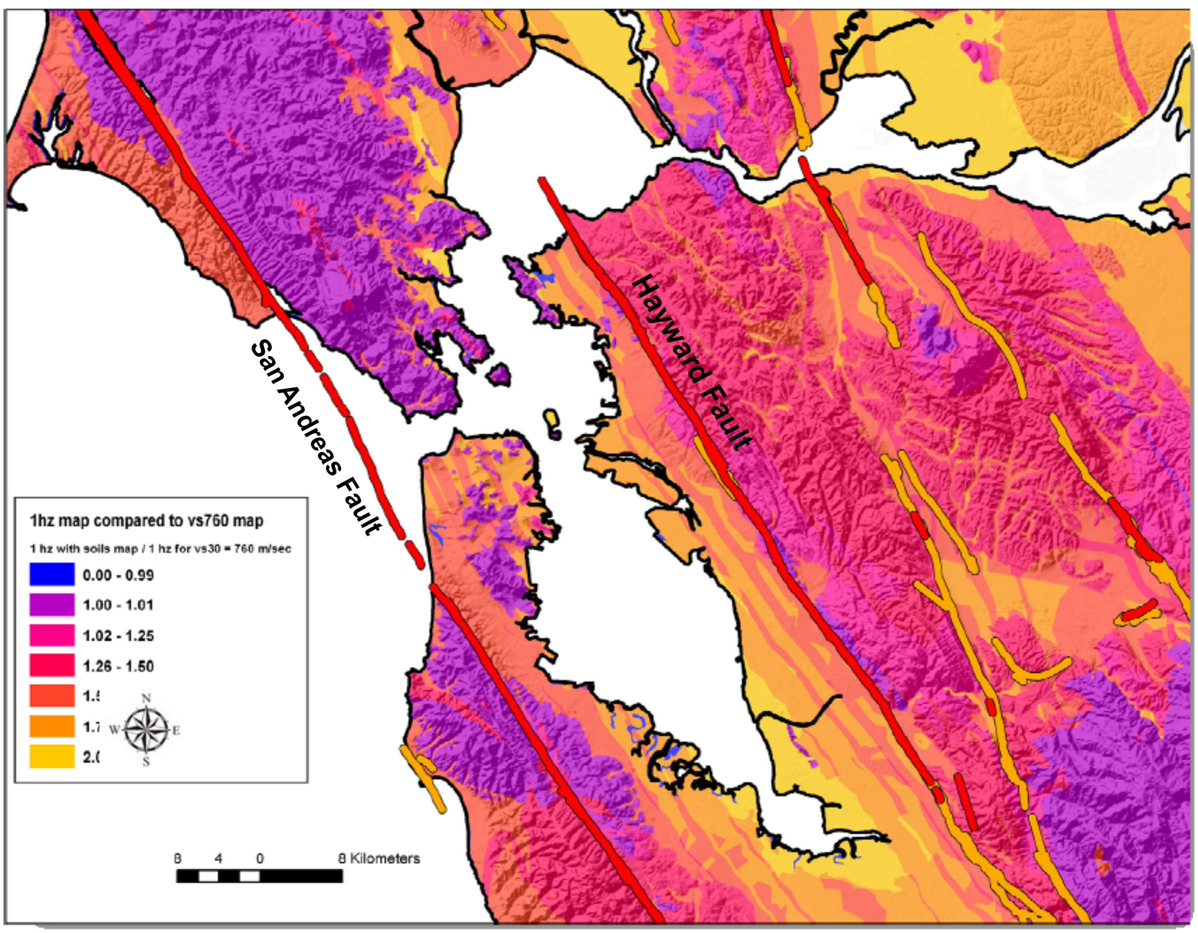


Figure 6. Soil amplification map with respect to V_{S30} = 760 m/sec. Map is for SA at 1.0 sec considering 2% probability of exceedance in 50 years; it is obtained by taking the ratio of hazard values based on variable V_{S30} to those based on V_{S30} = 760 m/sec (uniform rock).

CGS Map Sheet 48 is intended to show seismic shaking hazard in a single graphically simple image that allows non-scientists to understand the overall distribution of seismic shaking hazards, including the effects of amplification by near surface soils. Underlying the map is the most complete seismic hazard model developed through a broad-based consensus process and the most up-to-date, peer-reviewed estimate of the shear-wave velocity of the near-surface soils. The map itself can help planners and emergency preparedness officials evaluate the relative hazards across the state so that hazard mitigation efforts can be focused on the most hazardous areas.

The hazard maps presented in this article including Map Sheet 48 can be downloaded online at http://nsmp.wr.usgs.gov/ekalkan/California/index.html

ACKNOWLEDGMENTS

We wish to thank Steve Harmsen for his generous support on the latest version of the NSHMP seismic hazard code. Special thanks go to Mehmet Çelebi and Ross Stein for reviewing this article.

REFERENCES

American Society of Civil Engineers (ASCE) 2000. Prestandard and Commentary for the Seismic Rehabilitation of Buildings, prepared for the SAC Joint Venture, published by the Federal Emergency Management Agency, FEMA-356, Washington D.C.

Anderson, J. G., Bodin, P., Brune, J. N., Prince, J., Singh, S. K., Quass, R., and Onate, M., (1986). Strong ground motion from the Michoacan, Mexico, earthquake, Science 233, 1043–1049.

Boore, D. M. and Atkinson, G. (2008). Ground-Motion Prediction Equations for the Average Horizontal Component of PGA, PGV, and 5%-Damped PSA at Spectral Periods between 0.01 s and 10.0 s, Earthquake Spectra, 24, no. 1, 99-138.

Borcherdt R.D., (2002). “Empirical Evidence for Site Coefficients in Building Code Provisions” Earthquake Spectra, V. 18, N. 2, p. 189-217.

California Geological Survey, (2008). Earthquake shaking Potential for California, Map Sheet 48 (Available online at http://www.conservation.ca.gov/cgs/information/publications/ms/Documents/MS48_revised.pdf).

Campbell, K. and Bozorgnia, Y. (2008). NGA Ground-motion Model for the Geometric Mean Horizontal Component of PGA, PGV, PGD and 5% Damped Linear Elastic Response Spectra for Periods Ranging from 0.01 to 10 s, Earthquake Spectra, 24, no. 1, 139-171.

Chiou, B. and Youngs, R. (2008). An NGA Model for the Average Horizontal Component of Peak Ground-motion and Response Spectra, Earthquake Spectra, 24, no. 1, 173-215.

Holzer, T. L., (1994). Loma Prieta damage largely attributed to enhanced ground shaking, EOS Trans. Am. Geophys. Union 75 (26), 299–301.

Petersen, Mark D., Frankel, Arthur D., Harmsen, Stephen C., Mueller, Charles S., Haller, Kathleen M., Wheeler, Russell L., Wesson, Robert L., Zeng, Yuehua, Boyd, Oliver S., Perkins, David M., Luco, Nicolas, Field, Edward H., Wills, Chris J., and Rukstales, Kenneth S., (2008), Documentation for the 2008 Update of the United States National Seismic Hazard Maps: U.S. Geological Survey Open-File Report 2008–1128, 61 p.

Seekins, L. C., Boatwright, J., and Fumal, T., (2000). Soil Type and Shaking Hazard in the San Francisco Bay Area, U.S. Geological Survey: Available online at http://quake.wr.usgs.gov/hazprep/soil–type/.

Wills, C. J., Petersen, M., Bryant, W. A., Reichle, M., Saucedo, G. J., Tan, S., Taylor, G., and Treiman, J., (2000). A site-conditions map for California based on geology and shear-wave velocity, Bull. Seismol. Soc. Am. 90 (6B), S187–S208.

Wills,C.J. and Clahan, K.B., (2006). Developing a map of geologically defined site-condition categories for California: Bulletin of the Seismological Society of America, V. 96 p. 1483 – 1501.

Working Group on California Earthquake Probabilities, (2008). The Uniform California Earthquake Rupture Forecast, Version 2 (UCERF 2): U.S. Geological Survey Open-File Report 2007-1437 and California Geological Survey Special Report 203 [http://pubs.usgs.gov/of/2007/1091/].