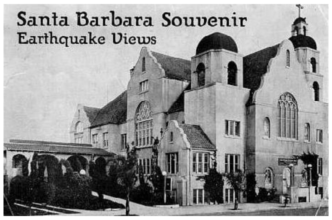

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INVESTIGATION OF GEOGRAPHIC RULES FOR IMPROVING SITE-CONDITIONS MAPPING

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ABSTRACT

We have used correlations between geologic units and shear wave velocity to complete a map of California showing geologic units that can be defined by their shear-wave velocity (Wills and Clahan, 2006). Preparation of this map raised a number of questions on how best to distinguish units within younger alluvium and the variability of shear-wave velocity in “hard” crystalline rock. In this study we have attempted to answer some of these questions by subdividing the young alluvium using different geographic rules within a GIS, then testing the rules by comparing the mean and standard deviation in Vs30. The goal of this study was to find simple rules that can be used to improve the current map, and be consistently applied in other regions to create site-conditions maps.

Wills et al.’s (2000) site-condition map for California provided a significant improvement in site characterization. It has been found to correlate with seismic amplification (Field, 2000) and has been adopted as a standard depiction for many applications of seismic shaking estimates (ShakeMap for example). Our work for the NGA project attempted to improve the resolution of the previous map by applying the shear-wave velocity characteristics of geologic units, similar to the units described by Wills and Silva (1998), to all sites in the NGA database. The definition of units by geologic factors, rather than grouped according to NEHRP velocity class, reduced the variability within many of the map units. This effort resulted in a set of 17 generalized geologic units that can be described by their shear-wave velocity and a map of California showing those units (Wills and Clahan, 2006). We used this map to estimate the Vs30 for all sites in the NGA database. These improved site characterizations based on Vs30 were used in the development of the new attenuation equations by all the NGA development teams. Although the current statewide map appears to work, in terms of separating units with different Vs30, application to other areas would be simpler if the simple geographic rules used in separating units within the young alluvium were shown to provide the optimum separation of units and could be defined so that they could be easily applied though a GIS. In this study we have examined the effectiveness of two factors, slope and distance from rock outcrop, for distinguishing higher from lower velocity alluvial deposits. Both slope and distance from rock should correlate with velocity, because of the typical decrease in stream power, and thus a decrease in both slope and grain size of the deposit with distance from a mountain front.

INTRODUCTION

This project attempts to contribute to improving characterization of the near-surface conditions of sites throughout California by developing geographic rules that may be used with geologic maps of California and potentially extended to other areas. Explaining the variations in seismic shaking because of site conditions has been an ongoing research topic for over 20 years. Tinsley and Fumal (1985) assigned individual shear-wave velocities to each geologic unit in their test area, taking into account age, grain size and depth. In 1994, the Northridge earthquake resulted in unexpected variations of damage and ground motions in and around the Los Angeles area. Immediately, a number of studies were launched to study ground motions in southern California. Park and Elrick (1998) extracted the shear wave velocity average to 30 m depth, Vs30. Their results show that Vs30 varies with grain size and age, and accordingly grouped the geologic units in southern California into eight different categories. Similarly, Wills and Silva (1998) assembled a database of shear-wave velocity measurements and correlated those with the materials described in borehole logs.

Wills et al. (2000) published a site-conditions map for all of California based on the NEHRP Vs30 categories, correlation of geologic units with Vs30 from Wills and Silva (1998) and generalization of the statewide 1:250,000 scale geologic maps. The "preliminary site conditions map" of Wills et al (2000) was found to correlate with seismic amplification (Field, 2000) and represented a credible first approximation for consideration of site conditions in seismic hazard estimates. Wills et al (2000) noted two main problems with this map: the lack of precision inherent in using the 1:250,000 scale geologic maps and the range of Vs30 in young alluvium due to variations in thickness, grain size and possibly regional differences in deposition and weathering.

More recent work by Wills and Clahan (2006) attempted to outline areas corresponding to geologic units with distinct Vs30. This effort provided an estimate of Vs30 for use in the Pacific Earthquake Engineering Research Center's Next Generation Attenuation Equation (NGA) project by applying the shear-wave velocity characteristics of geologic units, similar to the units described by Wills and Silva (1998), to all sites in the NGA database. This effort resulted in a set of 17 generalized geologic units that can be described by their shear-wave velocity and a map of California showing those units. One key change in this map from previous maps is that we sub-divided areas of young alluvium thought to be homogenous in Vs30. Generally, sub-categories of young alluvium were defined geographically, rather than by using detailed geologic information. The geographic rules were kept as simple as possible: alluvium is expected to be thin in narrow valleys and small basins, coarse near the base of steep mountains, and deep in the center of major basins. Using these rules, applied "by eye", the map prepared by Wills and Clahan (2006) separates geologic units within the young alluvium that appear to have different shear wave velocity (Table 1). Deep basins with an abundance of shear wave velocity information, the Imperial Valley and the Los Angeles basin, also can be shown to have significant regional differences in Vs30. Estimates of the mean and standard deviation of Vs30 from this map were provided to the NGA equation developers. All of the five attenuation equation developer teams used estimates of Vs30, measured at the strong-motion instrument site or from this map, as their primary term for site conditions. The developer teams found that the Vs30 values from the new map were more effective in reducing the residuals in the

Table 1, Geologic units and shear-wave velocity characteristics developed by Wills and Clahan, 2006.

Geologic Unit	**Geologic Description**	**Number of profiles**	**Mean Vs30**	**Std. Dev.**	**Vs30 from Mean of ln**	**Std. Dev. of ln**
Qi	Intertidal Mud, including mud around the San Francisco Bay	20	160	39	155	0.243
af/qi	Artificial fill over intertidal mud around San Francisco Bay.	44	217	94	202	0.357
Qal, fine	Quaternary (Holocene) alluvium in areas where it is known to be fine.	13	236	55	229	0.238
Qal, deep	Quaternary (Holocene) alluvium in areas where it is more than 30m thick.	161	280	74	271	0.250
Qal, deep, Imperial V	Quaternary (Holocene) alluvium in the Imperial Valley	53	209	31	207	0.135
Qal, deep, LA Basin	Quaternary (Holocene) alluvium in the Los Angeles basin.	64	281	85	270	0.275
Qal, thin	Quaternary (Holocene) alluvium in narrow valleys, small basins, and adjacent to the edges of basins.	65	349	89	338	0.244
Qal, thin, west LA	Quaternary (Holocene) alluvium in part of west Los Angeles.	41	297	45	294	0.150
Qal, coarse	Quaternary (Holocene) alluvium near fronts of high, steep mountain ranges and in major channels.	18	354	82	345	0.223
Qoa	Quaternary (Pleistocene) alluvium	132	387	142	370	0.273
Qs	Quaternary (Pleistocene) sand deposits.	15	302	46	297	0.171
QT	Quaternary to Tertiary (Pleistocene - Pliocene) alluvial deposits.	18	455	150	438	0.266
Tsh	Tertiary (mostly Miocene and Pliocene) shale and siltstone units.	55	390	112	376	0.272
Tss	Tertiary (mostly Miocene, Oligocene, and Eocene) sandstone units.	24	515	215	477	0.386
Tv	Tertiary volcanic units.	3	609	155	597	0.240
Kss	Cretaceous sandstone of the Great Valley Sequence in the central Coast Ranges.	6	566	199	539	0.332
serpentine	Serpentine.	6	653	137	641	0.204
KJf	Franciscan complex rock.	32	782	359	712	0.432
xtaline	Crystalline rocks, including Cretaceous granitic rocks, and metamorphic rocks.	28	748	430	660	0.489

ground motion than broader Vs categories based on NEHRP categories.

Like previous steps toward improved site-conditions mapping, preparation of the map by Wills et al (2006) has raised a series of questions:

- Is there a clear distinction based on the size of basin or width of valley that could do as well or better than the current visual classification of areas where thin alluvium affects Vs30?
- Can the higher velocities in “coarse alluvium” be related to geographic position at the base of high mountains or could they be due to soil formation in desert environments? Is it possible to separate these two effects?
- Can other geographic rules (e.g. distance from bedrock, slope, or surface roughness) do as well or better at differentiating Vs30 in alluvium?
- Are there systematic variations in Vs among “crystalline rocks”? Can those be correlated with slope, surface roughness or other geographic criteria?
- How much can we improve estimation of Vs30 by using higher resolution geologic maps?

DEVELOPING MAPS OF SHEAR WAVE VELOCITY BASED ON GEOLOGIC MAPS

Geologic maps use age, environment of deposition and grain size to define units. Although the physical properties that control shear-wave velocity, such as grain size, density, and fracture spacing do tend to vary between geologic units, they are not the defining criteria for most geologic units. As a result, there are numerous geologic units with essentially the same shear-wave velocity characteristics and considerable variability within most geologic units. For some classes of units, Tertiary shale for example, Vs30 values vary over a relatively small range, and the predicted variation in seismic amplification is small enough that the average Vs30 is a useful predictor of amplification on that type of materials. The challenge in preparing a map of shear-wave velocity based on geologic maps is to group those units that have similar velocity.

To prepare the statewide map of shear-wave velocity units, Wills et al (2000) and Wills and Clahan (2006) generalized from small-scale geologic maps that cover the state, grouping units with similar physical properties. One way to create more accurate and precise maps of shear-wave velocity is to start with more detailed geologic maps. Using larger-scale geologic maps ensures more precision in the location of contacts between geologic units and more accuracy in the description of geologic units, and in their assignment to shear-wave velocity classes. To test the potential improvements from using detailed geologic maps, we compiled geologic maps covering the Los Angeles basin and surrounding mountains and valleys. The geologic maps from Morton and Miller (2006), Saucedo et al (2003) and work in progress on the Los Angeles 1:100,000 scale quadrangle (California Geological Survey, in progress) have been prepared from mapping conducted at 1:24,000 scale or larger and represent the most detailed available mapping for the area. The geologic units have been grouped into the shear-wave velocity units of Wills and Clahan (2006), Two significant changes result from using these more detailed geologic maps, as illustrated in figure 1. The first is that areas of young alluvium are more extensive on the more detailed maps. The second is that many of the Tertiary bedrock units that had been grouped with Tertiary shale in the generalized statewide map are Tertiary sandstone on more detailed maps.

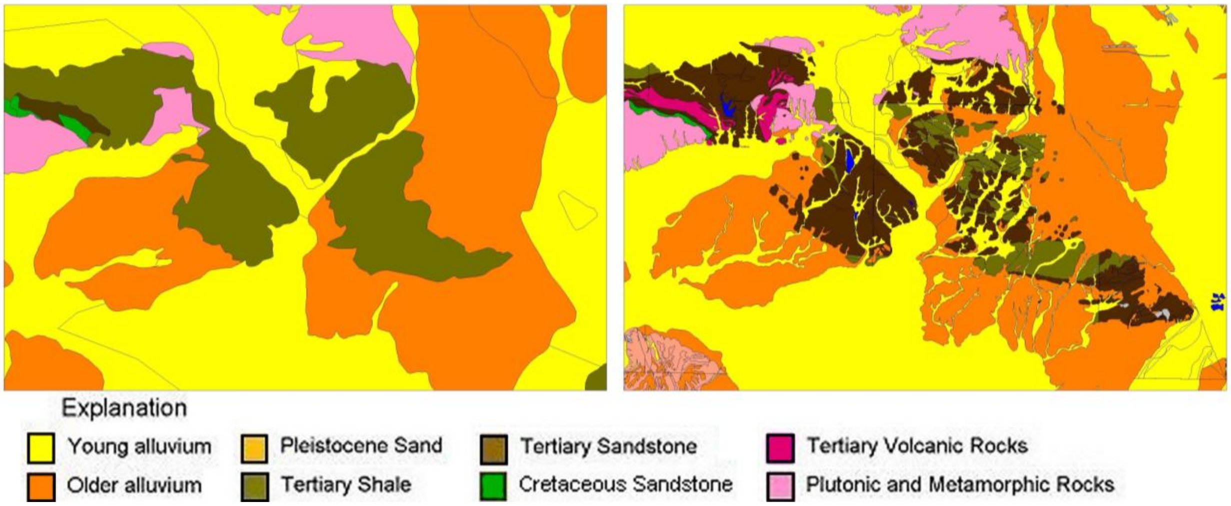


Fig. 1. Examples of the difference in using more detailed geologic maps in preparation of shear-wave velocity maps. These two maps show the Los Angeles and Hollywood 7.5 minute quadrangles, some of the most densely populated parts of the Los Angeles region. The area shown is about 15 miles across. The left map is from the statewide map prepared by Wills and Clahan (2006), based on small-scale geologic maps. The right map is based on 1:24,000 mapping by Mattison and Loyd (1998a,b).

More young alluvium is commonly shown on more detailed maps because narrow areas of alluvium in mountainous areas are simplified out of small-scale maps. In the Los Angeles area, the large-scale maps show more young alluvium in mountain valleys and particularly in the hills east of downtown Los Angeles. Within the Los Angeles region as shown on figures 7 and 8, the area of young alluvium on the more detailed maps is 4% larger than the area shown on the generalized maps. This increase represents 110 square kilometers, most of which had been mapped as bedrock. Most of the areas are thin alluvium in narrow valleys or at the base of mountains, so would have velocities higher than alluvium in the deep basins, but lower than most bedrock.

Tertiary sedimentary rocks were divided into sandstone and shale for the preliminary shear-wave velocity map of California (Wills et al, 2000) based on units shown on the 1:250,000 scale Geologic Atlas of California, completed between 1958 and 1972, and a few more recent maps. The units on the Geologic Atlas are defined by time, rather than lithology, however. Wills et al (2000) grouped all Paleocene, Eocene, and Oligocene as sandstone, and Miocene and Pliocene rocks as shale. As a statewide generalization, more of the early Tertiary rocks are sandstone, and more of the late Tertiary are shale. In detail, however, there are many areas where this generalization is not correct. In the Los Angeles area, this generalization resulted in sandstones of the Topanga, Puente and Fernando Formations, among others, being grouped with shale. With the more detailed maps, and designations based on lithologic descriptions of the individual units, the area mapped as shale is only 40% of the previous map, while the area mapped as sandstone went up by over 3 times.

Based on the above comparison in the Los Angeles area, detailed geologic maps result in more accurate maps of shear-wave velocity both because of the inherent increase in the precision of the mapping, but also because of the ability to test and revise simplifying assumptions that are required when working with more generalized maps.

Developing maps of Shear Wave Velocity in Alluvial Basins

Differentiating shear-wave velocity units is most important in recently deposited materials, because these materials tend to have lowest velocities and therefore the greatest potential for seismic amplification. Recent deposits also underlie basins and plains where people tend to settle and urban centers grow. Variation in amplification because of variation in shear wave velocity across an urban area can have a significant effect on earthquake damage and losses.

In some cases, there is a simple correspondence between geologic unit characteristics and velocity. For example, estuarine or marsh deposits tend to be rapidly deposited (low density) silt and clay. Because estuarine deposits are recognized as having different properties from the surrounding deposits, they are usually mapped as geologic units. They also have a narrow range of shear-wave velocity so they, “bay mud” and “intertidal mud”, have long been recognized as areas of enhanced seismic shaking. Other geologic units, alluvial fan deposits in particular, can have a wide range of density and grain size. The factor of two range of Vs30 in recent alluvial deposits, from about 200 to about 400 m/s, overlaps the range of “bay mud” at the low end and the range of “soft rock” at the high end. This range in Vs30 results in a range of amplification that is also about a factor of two (graphs in Wald and Mori, 2000). This range in velocity is related to the density and grain size of the deposit, as well as soil forming processes that, with time, can increase velocity by filling pore spaces with clay or calcium carbonate or decrease velocity by weathering of large clasts.

Although the factors that lead to the large range of shear-wave velocity in recently deposited alluvium are well recognized, a poor correlation between geologic (or “soils”) map units has repeatedly been noted. Thelen et al. (2006) showed that fifty measurements of Vs30 in coarse alluvium of the northern San Gabriel Valley had an average velocity above the range of the NEHRP- based CD class predicted, and large variance. In Las Vegas and Reno, Nevada, Scott et al. (2004, 2005) found poor Vs30 predictability from mapped alluvial units. Park and Elrick, (1998), and Steidl, (2000) attempted to correlate geologic maps of southern California with seismic amplification, without much success. Steidl did not even find significant differences in amplification between younger and older alluvium, probably because of the way those units were defined and mapped on the maps that he used in his study.

There may be many reasons for poor correlation between mapped geologic units and Vs30 in Quaternary deposits, but some basic reasons can be inferred from the nature of geologic maps of Quaternary deposits and the methods by which they are made. Geologic maps use divisions of geologic time as the first level discriminator between units. This is useful because “older alluvium” or “Pleistocene alluvium” commonly includes all alluvial deposits where soil-forming processes, compaction, and cementation have significantly raised the shear-wave velocity. Older alluvium also has a narrow enough range of Vs30 that it is mapped as a single site-condition category on the map of Wills and Clahan (2006). Geologic maps use environment of deposition as the second level discriminator between geologic units. This can be useful when environment of deposition leads to a narrow range of grain size and density, as in estuarine deposits discussed above. Recent alluvial fan and basin deposits are commonly mapped as “Younger alluvium” or “Holocene alluvium”. These deposits underlie areas of active or recently active deposition of sediment, with slight or no modification due to cementation or weathering. Because these deposits underlie large areas within urban regions, several methods have been developed to further sub-divide these units. Third-level discriminators of geologic units within young alluvial fans are most commonly based on age, commonly with additional descriptors based on grain size. These subdivisions within recent alluvial fan deposits depend on interpretations of the relative age of geomorphic surfaces and on descriptions of the near-surface materials from boreholes or test pits.

The subdivisions within Holocene (Recent) alluvial fan deposits have proven most problematic for correlating between geologic maps and shear-wave velocity. It seems clear that geologic maps show detailed units within areas of young alluvium, and that those may also designate a typical grain size of those units. Since grain size is the main physical difference between alluvial deposits with different shear-wave velocity, these units should correlate with Vs30. The most common result of studies to examine this correlation is that areas mapped as coarse alluvium have no significant difference from those mapped as fine alluvium (Park and Elrick, 1998, Steidl, 2000, Scott, 2004, 2005). This disappointing result has led some to doubt the value of geologic maps for estimating Vs30. This result is not surprising, however, when one considers how these maps are made and the patterns of deposition of materials on alluvial fans. Geologic maps that show variations in grain size in recent alluvium are almost always based on information from the upper few meters of the deposits. On alluvial fans the locations of channels, where coarser materials are deposited, moves across the fan over time. In cross section, deposits tend to be a mass of the average grain size of the fan with lenses of coarser grained materials representing the channel deposits. Any point on the fan may be underlain by material representing sheet flooding over the body of the fan as well as channel deposits. The proportions of those materials do not change depending on whether a coarser channel deposit happens to be at the surface. As a result, grain size designations based on the materials at the surface are commonly not representative of the average of the materials within the upper 30 m.

An additional problem in correlating the material at the surface, and represented on geologic maps, with Vs30 is that Holocene alluvium is rarely 30m thick. Where the young alluvium is thinner, Vs30 can be strongly influenced by the underlying material. This can be a significant issue when alluvium at the surface is underlain by material with much higher velocity, such as crystalline bedrock. Fortunately, locations where “thin alluvium” is found can be anticipated. Wills and Clahan (2006) designated areas at the edges of large basins and in narrow valleys as “thin alluvium” based only on distance from the basin edge. A boundary drawn a few km from the edges of most alluvial basins in California did separate measured profiles in “deep alluvium” with a mean Vs30 of about 280 m/s from those in “thin alluvium” with a mean Vs30 of about 350 m/s.

Young alluvium is typically deposited in a subsiding basin. Since such basins have formed over much longer time scales than the Holocene, younger alluvium at the surface is typically underlain by older alluvium with similar properties. In this typical case, where young alluvium overlies older alluvium, the thickness of the young alluvium appears to be less significant. In the west Los Angeles area, 41 shear-wave velocity profiles have been measured in an area where geologic logs clearly document less than 30 m of young alluvium underlain by older alluvium. The mean Vs30 for this area is not significantly different from the mean Vs30 for deep alluvium in the Los Angeles basin, or from deep alluvium in other basins in California (Wills and Clahan, 2006).

Any system to predict the Vs30 in young alluvial deposits needs to consider several concepts: 1) differences in Vs in young alluvial deposits correlate with grain size. Compaction, soil formation and cementation have lesser effects. 2) Grain size of the surface material does not reliably indicate the average grain size in the upper 30 m. 3) Grain size does generally decrease downstream from the apex of an alluvial fan. 4) Slope of alluvial fans also decrease downstream from the apex, so there should be a positive correlation between slope and average grain size. 5) The thickness of the young alluvial deposits has a significant effect on Vs30 when harder material is within 30 m of the surface, the effect does not appear to be significant when the young alluvium is underlain by older alluvium.

Wills and Clahan (2006) made use of these concepts in developing their geologically-based Vs30 map of California. In this study we hope to refine the rules they used in making that map, examine the relative importance of different factors, and apply the rules that best distinguish Vs30 categories to detailed geologic maps.

Since grain size at the surface of an alluvial fan deposit has only slight predictive power for the average grain size in the upper 30 meters, and does not distinguish areas where the alluvium is less than 30 m thick, an alternate method is needed to distinguish Vs30 units in young alluvium. Two methods have been attempted: either a detailed three-dimensional model showing the variation in thickness of deposits with different velocity can be constructed, or some useful proxy must be found for the average grain size within an alluvial fan deposit. Tinsley and Fumal (1985) and Holzer et al, (2005) have shown that three-dimensional models showing the thickness of layers with differing velocity can be used to predict Vs30, or other parameters, across parts of the Los Angeles and San Francisco-Oakland urban areas. Constructing a three-dimensional velocity model of the upper 30 m is very time and data intensive, however, so if site-conditions maps of large areas are needed, a useful proxy for average grain size must be found.

For this study we tested two potentially useful proxies for Vs30 in young alluvium. Both take advantage of the decrease in the average grain size within alluvial fan deposits with distance from the apex of the fan. Since the apex of the fan, the point where the stream begins to deposit material, commonly coincides with a mountain front, grain size typically decreases with distance from the mountain front. Similarly, the stream’s gradient, and its ability to transport material, decreases away from the mountain front. The result is relatively steep, coarse-grained deposits near the mountain front grading into less steep, finer grained alluvial deposits farther away. The distal alluvial fan deposits may grade into basin, marsh, lake, or fluvial deposits that have still lower gradients. A system for dividing young alluvial deposits by average grain size could take advantage of the decrease in grain size with distance from the source or the decrease with stream gradient (slope of the surface of the fan).

For the map of Wills and Clahan (2006), young alluvium is divided into eight different categories: Qal, fine; Qal, deep; Qal, deep, Imperial V; Qal, deep, LA Basin; Qal, thin; Qal, thin, west LA; and Qal, coarse. These categories take advantage of the general velocity gradient away from mountain fronts, and the available subsurface data that shows where the alluvium in the subsurface is generally fine, or shows that alluvium in one basin (the Imperial Valley) has lower velocity than other basins in the state. In order to test more general rules for subdividing the younger alluvium, we have combined all these mapped categories into one, then split that map unit based on geographic rules that may be useful proxies for grain size and Vs30. The overall goal is to find methods that result in well-defined, reproducible polygons that have smaller ranges of Vs30 than the interpretive polygons of Wills and Clahan (2006). For this analysis we are using the same database of Vs30 measurements as that earlier work.

Variability of Vs30 in young alluvium with distance from rock. In reviewing the measured shear wave velocity in young alluvium. Wills and Silva (1998) noted that near the edges of alluvial basins Vs30 tended to be higher and much more variable, largely because some 30 m profiles included young alluvium over higher velocity material. This led Wills and Clahan (2006) to establish a unit they called "thin alluvium" designated simply by assuming that the alluvium in narrow valleys, small basins and close to the edges of larger basins may be less than 30 m thick. The geographic limits of this were drawn "by eye". The Vs30 in "thin alluvium" designated in this way does appear to be higher and more variable in Vs30 than "deep alluvium" (Table 1). Unfortunately, because the geographic extent of these areas were drawn approximately based on individual judgment, application to other areas is difficult. In order to apply the same rules in a more systematic way, we have tested the variability of Vs30 in young alluvium with distance from "rock".

To test variability of Vs30 in young alluvium with distance from rock, we used the digital map of Wills and Clahan (2006) and drew polygons enclosing areas within 1, 2, 5, and 10 km from rock. We included Tertiary sandstone and shale, Franciscan and other Cretaceous rocks, and all metamorphic, volcanic and plutonic rocks in the "rock" category. Older alluvium and Plio-Pliestocene alluvial units were not included as "rock". A distance category corresponding to one of these polygons was then applied to each site where shear-wave velocity has been measured. Sorting the Vs30 measurements by distance category yields the values shown in Table 2 and Figure 2.

Table 2. Vs30 values in young alluvium sorted by distance from rock

	0-1 km	1-2 km	2-5 km	5-10 km	>10 km
Mean	328.7	314.0	298.0	262.0	212.8
Standard Deviation	96.5	67.3	63.2	59.8	31.6
Minimum	190	212	172	151	163
Maximum	629	453	457	478	318
Number of profiles	107	51	59	68	64

As expected, mean Vs decreases with distance from rock. The variability in Vs30 also appears to decrease significantly with distance. The decrease in variability is most apparent between sites from 0-1 km and those from 1-2 km, suggesting that sites more than 1 km from the edge of an alluvial basin are much less likely to encounter higher-velocity material within 30 m of the surface. Variability of Vs30 in young alluvium also appears to decrease at distances of over 10 km from rock. This may be due to the alluvial deposits more than 10 km from rock being basin and floodplain deposits composed of silty sand and clay.

Variability of Vs30 in young alluvium with slope. Another option for subdividing young alluvial deposits is to sort them by the slope of the ground surface. Slope reflects the stream gradient, and therefore the stream's ability to transport material. Thelen et al, (2006), noted that for a series of Vs profiles along the San Gabriel River across the Los Angeles basin, Vs30 was proportional to stream power. On a much larger scale, Wald and Allen, (2007) proposed that surface slope in all materials could be a useful proxy for Vs30. Although Wald and Allen show a correlation between slope and Vs30, and this appears to be a useful first approximation, the

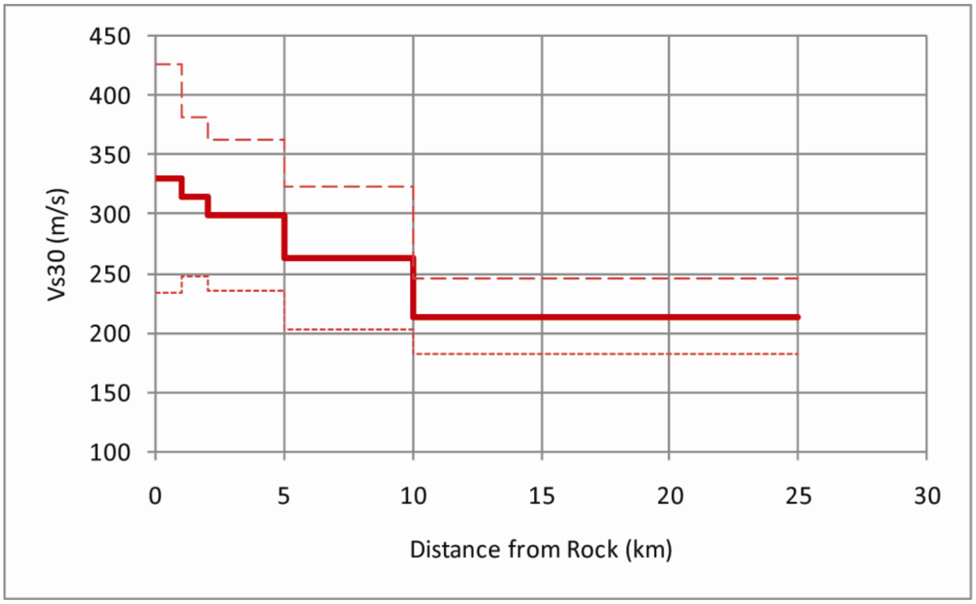


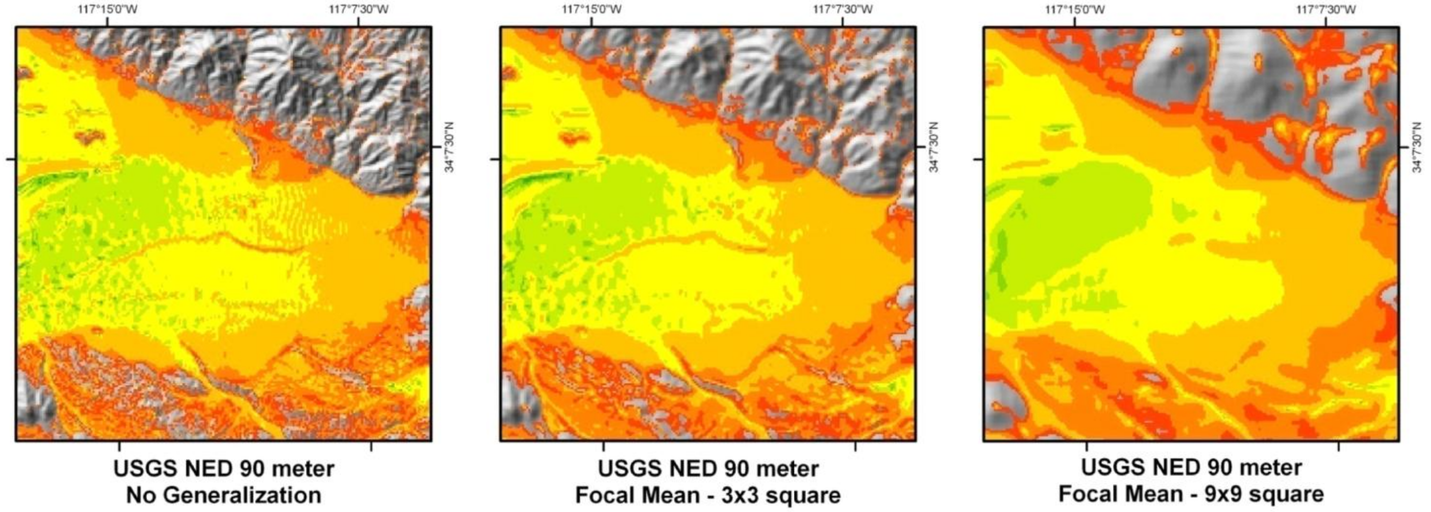
Fig. 2. Variation of Vs30 with distance from rock

correlation probably reflects a number of separate causes. In depositional areas, the correlation between slope and Vs30 probably reflects stream power, as proposed by Thelen et al. In erosional areas, in contrast, slope may reflect the surface material's resistance to erosion. Although both of these factors may lead to a correlation between higher velocity and steeper slopes, we have examined the correlation of Vs30 with slope in young alluvium (in depositional settings) not the correlation of Vs30 with slope in bedrock (in erosional settings).

DEM Selection. In order to compare Vs30 to slope, we must first decide how to measure slope. Digital Elevation Models (DEMs) are digital representations of the earth's surface and are available at various resolutions and extents from various sources. For this study we chose to compare elevation data from the USGS National Elevation Dataset (NED) (available at http://ned.usgs.gov/) and NASA's Shuttle Radar Topography Mission (SRTM) (available at http://www2.jpl.nasa.gov/srtm/). These datasets are available in resolutions ranging from 10 to 90 meters (1/3 arc second to 3 arc second) and both cover the entire state of California.

In order to determine which dataset was better suited for the purpose of producing a statewide slope map, we generated preliminary shaded relief and slope maps using ESRI's Spatial Analyst for ArcGIS 9.2. A cursory review of the maps revealed that the 90 meter datasets produced a smoother generalized surface than the higher resolution data, which appeared to contain many unwanted artifacts. Therefore, the 90 meter USGS dataset was chosen for our slope analysis. The selected USGS dataset was derived from the USGS 1 arc-second (30 meter cell size), 1:24,000-scale seamless DEM. The statewide DEM was projected from Decimal Degrees to Albers conic, and resampled to a 90 meter cell size.

DEM Preparation. In many areas, the digital elevation data produced by the USGS is derived from the interpolation of contour lines. As a result "step-like" or "rice paddy" artifacts are visible on derivative shaded relief and slope maps. To reduce the effect of these artifacts and obtain a better estimate of slope, the 90 meter DEM grid was generalized by calculating the mean elevation value over a specified neighborhood of pixels and applying the calculated value to the central pixel. We generated three generalized slope grids using a 3x3, 5x5, and 9x9 pixel square and compared the results (Figure 3). The generalization processes were all effective in diminishing artifacts from the original dataset, but the 9x9 pixel square generalization produced the best definition of large scale geomorphic features such as alluvial fans and depositional basins.



USGS NED 90 meter
No Generalization

USGS NED 90 meter
Focal Mean - 3x3 square

USGS NED 90 meter
Focal Mean - 9x9 square

Fig. 3: Example of artifacts visible in preliminary slope maps derived from the original unmodified dataset and datasets resulting from the generalization process over a 3x3, and 9x9 pixel square.

Slope Map Generation. As described above, the USGS NED 90 meter DEM was prepared using a generalization process in order to remove artifacts inherent to the data. Spatial Analyst was then used to process the generalized DEM and create a grid depicting the percent slope for each pixel. The slope grid was originally reclassified into 12 classes as shown in Table 3 and graphically shown in figure 4. Upon examining the data, we found that were only a few or no profiles in the four flattest slope categories, so all measurements less than 0.1 percent slope were grouped into one category. The reclassified slope grid was then used to create a polygon shapefile from contiguous pixels of the same slope class using the “Convert Raster to Features” function in Spatial Analyst.

Table 3. Slope categories originally correlated with Vs30

Percent Slope	Number of profiles	Mean Vs30	Sd of Vs30
0 - 0.01	*		
0.01 - 0.02	*		
0.02 - 0.05	*		
0.05 - 0.1	21	224	34
0.1 - 0.2	43	227	47
0.2 - 0.5	61	248	54
0.5 - 1	75	303	74
1 – 2	49	320	91
2 – 5	58	356	86
5 - 10	14	353	87
10 - 15			
15 -			
* insufficient data, grouped with category below			

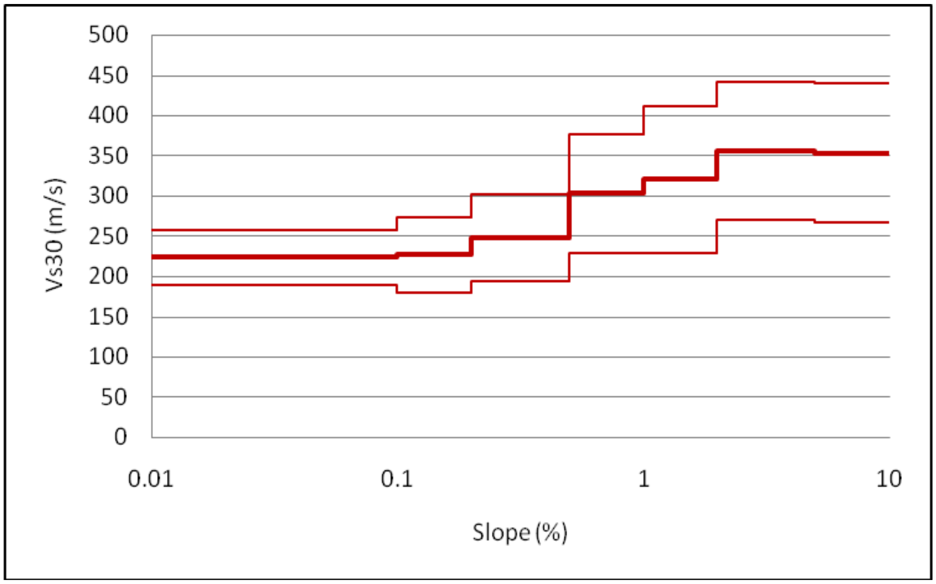


Fig. 4. Variation of Vs30 with slope, all categories shown

Based on our initial analysis, it appeared that the number of slope categories could be further reduced, and the resulting maps simplified. In depicting the boundaries of slope categories on geologic maps, we found that there appeared to be a coincidence between the 0.5% slope boundary from the slope map with the boundary on several maps between the lower ends of alluvial fans and adjoining basin or floodplain deposits. Vs30 between 0.5% and 1.0% appeared similar to Vs30 between 1.0% and 2.0% and Vs30 between 2.0% and 5.0% appeared similar to Vs30 between 5.0% and 10.0%. We therefore tested whether three simplified categories could subdivide the Vs30 in young alluvium. The results of that test are shown in Table 4 and Figure 5. Comparing the mean and standard deviation of Vs30 with the categories defined by Wills and Clahan (2006) (Table 1) shows that these simplified slope categories result in fewer ranges of Vs30 in young alluvium and ranges that have comparable standard deviations. This result for the California data, and the potential that the same slope categories can be used in other areas, suggest that these simplified slope categories can be used to develop the next generation map of shallow shear wave velocity.

Table 4. Simplified slope categories applied to mapping

Slope	Number of profiles	Mean Vs30	Sd of Vs30
≤0.5	169	231	55
0.5-2	124	306	78
>2	73	353	87

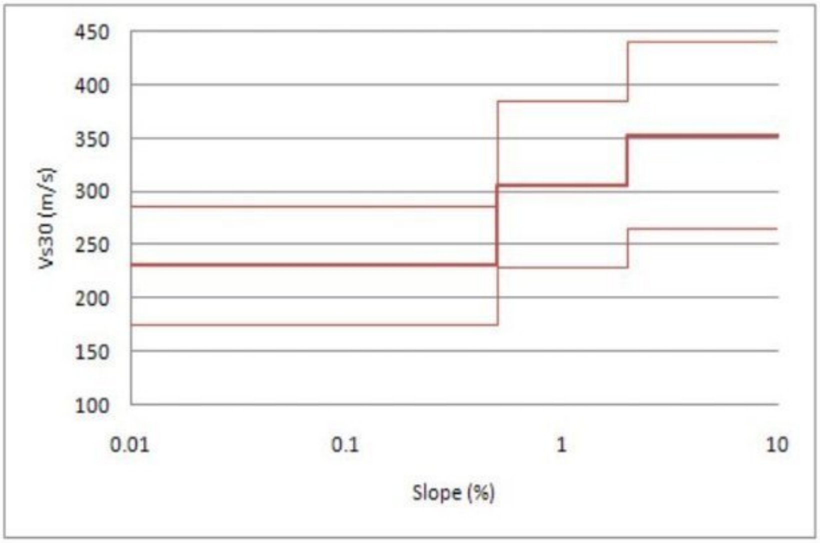
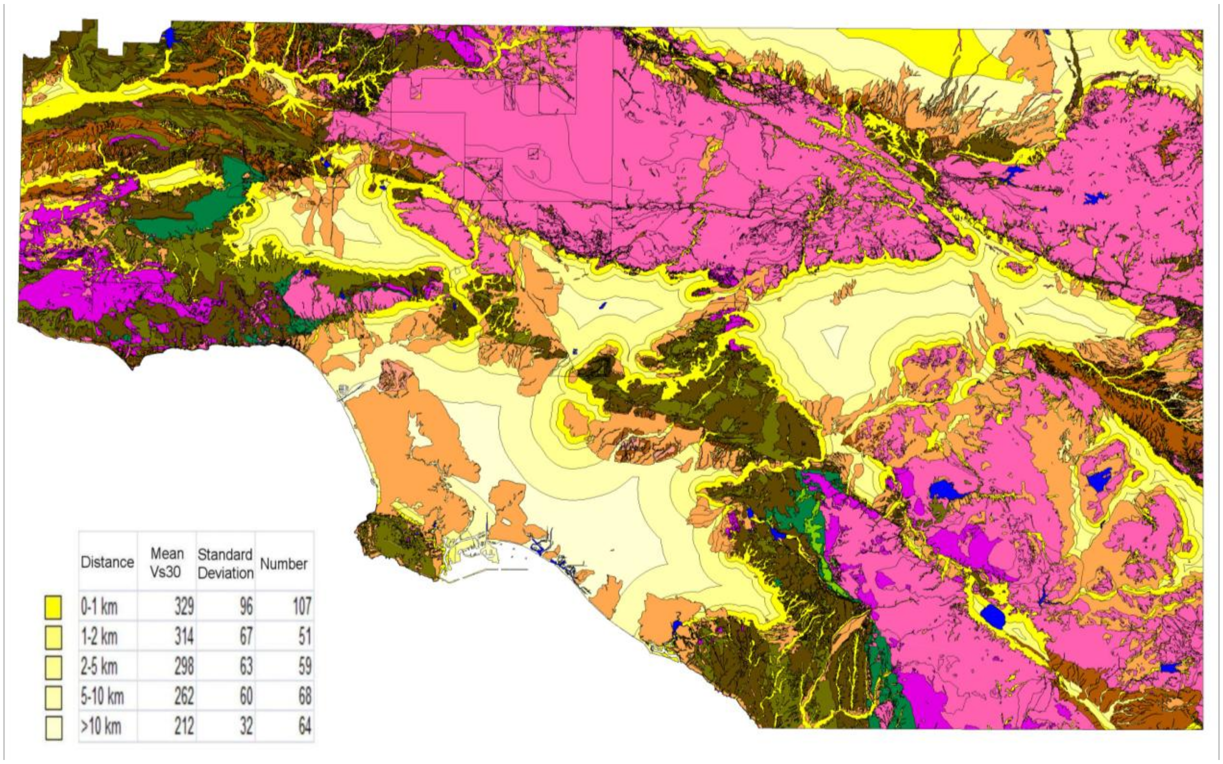


Fig. 5. Variation of Vs30 for three simplified slope categories

DISCUSSION

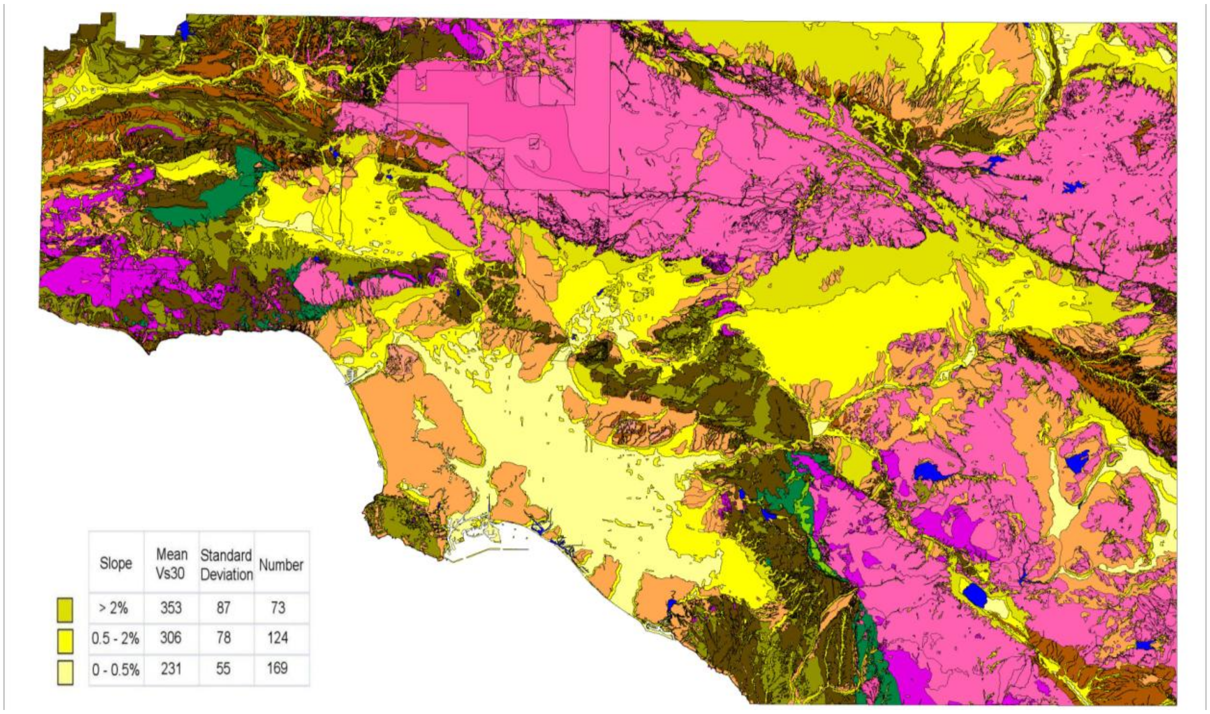
We have developed two rules that can be applied with available GIS data to develop maps of shear-wave velocity. Subdividing areas underlain by young alluvium either by distance from bedrock or by slope results in polygons with ranges of Vs30 values that are at least as well-defined as the ranges for polygons from the map of Wills and Clahan (2006). Either of these rules will allow completion of revised shear-wave velocity maps of California, or potentially of other areas, that define areas with specific ranges of Vs30 as well or better than the previous map.

One remaining question is which of these two rules results in the best definition of shear-wave velocity classes, and the best correlation with seismic amplification. A study of the correlation of either of these maps with seismic amplification is beyond the scope of this study, but correlations with other geological features suggest that sub-division based on slope is likely to provide better correlation with amplification. One distinct difference between the slope-based and the distance-based maps of the Los Angeles area (Figure 6 and Figure 7) is that the distance based rule results in concentric gradation of predicted Vs30 in the larger alluvial basins, while the slope based rule results in asymmetric gradation of predicted Vs30. The asymmetric slopes of the San Fernando, San Gabriel, and upper Santa Ana River basins are the result of large alluvial fans that have their sources in the San Gabriel and San Bernardino Mountains north of the Los Angeles Basin, and much smaller uplifts and resultant alluvial fans along the south sides of those basins. From the topography and mapped geology, there are steep, coarse-grained alluvial fans along the northern edges of these basins which grade to less-steep and finer-grained deposits to the south. In each of these basins, the finest-grained materials, and many of the low Vs30 measurements are along the southern edges of these basins where a distance from bedrock rule would predict relatively high Vs30. Although the statewide data set does not clearly distinguish the slope-based rule for subdividing young alluvium as better than the distance based rule, slope appears to correlate with grain size and possibly with Vs30 better in these asymmetric basins. Additionally, as noted above, the boundary on the slope maps between slopes steeper and less steep than 0.5% coincides with a boundary on some geologic maps between sandy and gravelly alluvial fan deposits and floodplain and basin deposits that are commonly finer grained. This coincidence suggests that a slope-based boundary may have better correlation with grain size than the distance-based boundaries.



	Distance	Mean Vs30	Standard Deviation	Number
🟨	0-1 km	329	96	107
🟨	1-2 km	314	67	51
🟨	2-5 km	298	63	59
🟨	5-10 km	262	60	68
☐	>10 km	212	32	64

Fig. 6. Preliminary map of shear-wave velocity in the Los Angeles region using detailed (1:24,000) geologic maps, distance from bedrock to classify younger alluvium and the classification of Wills and Clahan (2006) for other units. Young alluvium shown in shades of yellow, other units as defined on Figure 1. Using distance from bedrock and larger scale geologic maps results in better definition of velocity categories and more precision in location of boundaries than the previous statewide map.



	Slope	Mean Vs30	Standard Deviation	Number
🟨	> 2%	353	87	73
🟨	0.5 - 2%	306	78	124
🟨	0 - 0.5%	231	55	169

Fig. 7. Preliminary map of shear-wave velocity in the Los Angeles region using detailed (1:24,000) geologic maps, distance from bedrock to classify younger alluvium and the classification of Wills and Clahan (2006) for other units. Young alluvium shown in shades of yellow, other units as defined on Figure 1. Using slope and larger scale geologic maps results in better definition of velocity categories and more precision in location of boundaries than the previous statewide map.

Development of maps of potential seismic amplification depend on maps of shear-wave velocity in the shallow subsurface. Detailed three-dimensional models such as those of Holzer et al, 2005, which include the extent, thickness, and velocity of geologic units result in the most precise and accurate estimates of Vs, but are limited to small areas by the data required to construct such models. At the other end of the scale, the model of Wald and Allen (2007) gives a first-order estimate of Vs based only on a single data set that is available for the entire globe. This study is the latest in a series that attempts to use geologic maps to estimate Vs. Our intent is to be able to estimate Vs across a large urban region or an entire state. An intermediate scale mapping methodology is needed so that estimates can be more precise than those of Wald and Allen (2007), but much less data-intensive than those of Holzer and others (2005). It appears that the geologic categories of Wills and Clahan (2006), combined with the slope-based rule for sub-dividing younger alluvial deposits will allow the estimation of shallow Vs across large regions suitable for ShakeMap and other regional applications with enough precision that estimates of Vs can be used in studies of earthquake shaking, damage and losses.

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REFERENCES

Field, E.H. [2000], A modified ground motion attenuation relationship for southern California the accounts for detailed site classification and a basin depth effect, Bull. Seism. Soc. Am., Vol. 90, pp. S209-S22

Holzer, T.L., M.J. Bennett, T.E. Noce, and J.C. Tinsley, III, [2005], Shear-wave velocity of surficial geologic sediments in Northern California: Statistical distributions and depth dependence: Earthquake Spectra, Vol. 21, No. 1, p. 161-177.

Mattison, E., and R.C. Loyd, [1998], Liquefaction Zones in the Hollywood 7.5-Minute Quadrangle, Los Angeles County, California, California Geological Survey Seismic Hazard Report 026. 47 p. Accessed on CGS Seismic Hazard Zoning web page at http://gmw.consrv.ca.gov/shmp/download/evalrpt/holly_eval.pdf on 3/24/08

Mattison. E., and R.C. Loyd, [1998], Liquefaction Zones in the Los Angeles 7.5-Minute Quadrangle, Los Angeles County, California, California Geological Survey Seismic Hazard Report 029. 41 p. Accessed on CGS Seismic Hazard Zoning web page at http://gmw.consrv.ca.gov/shmp/download/evalrpt/la_eval.pdf on 3/24/08

Morton, D.M. and F.K. Miller, [2006], Geologic map of the San Bernardino and Santa Ana 30' x 60' quadrangles, California, with digital data preparation by Cossette, P.M., and Bovard, K.R.: U.S. Geol. Surv. Open-File Report 2006-1217

Park, S., and Elrick, S. [1998], Predictions of shear-wave velocities in southern California using surface geology, Bull. Seism. Soc. Am., Vol.. 88, 6 pp. 77-685.

Saucedo, G.J., H.G. Greene, M.P. Kennedy and S.P. Bezore, California, [2003], Geologic Map of the Long Beach 30' X 60' Quadrangle, California Geological Survey Regional Geologic Map Series, 1:100,000 Scale, Map No. 5, Version 1.0, Accessed on CGS Preliminary Geologic Map Web Page at ftp://ftp.consrv.ca.gov/pub/dmg/rgmp/Prelim_geo_pdf/lb_geol-dem.pdf , on 3/24/08

Scott, J. B., M. Clark, T. Rennie, A. Pancha, H. Park and J. N. Louie, 2004, A shallow shear-wave velocity transect across the Reno, Nevada area basin: Bull. Seism. Soc. Am., Vol. 94, No. 6, pp. 2222-2228.

Scott, J. B., T. Rasmussen, B. Luke, W. Taylor, J. L. Wagoner, S. B. Smith, and J. N. Louie, [2006], Shallow shear velocity and seismic microzonation of the urban Las Vegas, Nevada basin: Bull. Seismol. Soc. Amer., 96, No. 3

Steidl. J.H., [2000], Site Response in Southern California for Probabilistic Seismic Hazard Analysis: Bull. Seism. Soc. Am., Vol.. 90; No. 6B; pp. S149-S169.

Thelen, W. A., M. Clark, C. T. Lopez, C. Loughner, H. Park, J. B. Scott, S. B. Smith, B. Greschke, and J. N. Louie, [2006], A transect of 200 shallow shear velocity profiles across the Los Angeles Basin: Bull. Seism. Soc. Am., Vol. 96, No. 3, pp. 1055-1067

Tinsley, J. C., and Fumal, T. E. [1985], Mapping Quaternary sedimentary deposits for areal variations in shaking response: in *Evaluating Earthquake Hazards in the Los Angeles Region—An Earth Science Perspective*, Ziony, J. I. (Editor), U. S. Geol. Surv. Profess. Pap. 1360, 101-126.

Wald, D.J. and Allen, T.I., [2007], Topographic Slope as a Proxy for Seismic Site Conditions and Amplification, Bull. Seism. Soc. Am., Vol. 97; No. 5; pp. 1379-1395

Wald, L.A., and Mori, J., [2000], Evaluation of Methods for Estimating Linear Site-Response Amplifications in the Los Angeles Region: Bull. Seism. Soc. Am., Vol. 90; No. 6B; pp. S32-S42.

Wills,C.J. and Clahan, K.B., [2006], Developing a map of geologically defined site-conditions categories for California: Bull. Seism. Soc. Am., Vol. 96 pp. 1483 – 1501

Wills, C.J. and K. B. Clahan, [2004], NGA: Site condition metadata from geology: PACIFIC EARTHQUAKE ENGINEERING RESEARCH CENTER Project 1L05.

Wills, C., M. Petersen, W. Bryant, M. Reichle, G. Saucedo, S. Tan, G. Taylor, and J. Treiman [2000], A site-condition map for California based on geology and shear-wave velocity, Bull. Seism. Soc. Am. Vol. 90, pp. S187-S208.

Wills, C.J. and Silva, W., [1998], Shear wave velocity characteristics of geologic units in California: Earthquake Spectra, Vol. 14, pp. 533-556.