Mapping NEHRP V_{S30} Site Classes

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Site-amplification potential in a 140-km^2 area on the eastern shore of San Francisco Bay, California, was mapped with data from 210 seismic cone penetration test (SCPT) soundings. NEHRP V_{S30} values were computed on a 50-m grid by both taking into account the thickness and using mean values of locally measured shear-wave velocities of shallow geologic units. The resulting map of NEHRP V_{S30} site classes differs from other published maps that (1) do not include unit thickness and (2) are based on regional compilations of velocity. Although much of the area in the new map is now classified as NEHRP Site Class D, the velocities of the geologic deposits within this area are either near the upper or lower V_{S30} boundary of Class D. If maps of NEHRP site classes are to be based on geologic maps, velocity distributions of geologic units may need to be considered in the definition of V_{S30} boundaries of NEHRP site classes. [DOI: 10.1193/1.1895726]

INTRODUCTION

Local amplification of strong ground motion by shallow soils, which is commonly referred to as site amplification (Joyner and Boore 1988), is generally recognized as a significant seismic hazard. In some earthquakes, such as the 1985 Mexico City, Mexico, and 1989 Loma Prieta, California, earthquakes, site amplification has been a major factor in earthquake damage (Anderson et al. 1986, Holzer 1994). As a result, many U.S. building codes now require consideration of site amplification when estimating the seismic demand on a structure and rely on a time-averaged shear-wave velocity to a depth of 30 m (V_{S30}) for this evaluation (Borcherdt 2002, Dobry 2000, ICBO 2000).

Recognition of the importance of site amplification has also prompted efforts to map site conditions at regional scales. These maps are potentially useful for both code applications and input to earthquake loss models. Although early maps were qualitative (e.g., Borcherdt 1991), recent maps have been quantitative. For example, Seekins et al. (2000) and Wills et al. (2000) portray the geographic distribution of V_{S30}. The maps were based on geologic maps and regional compilations of shear wave velocity (V_S) of the mapped surficial geologic units. Neither map explicitly considered the effect of the thickness of surficial units on V_{S30}.

This article describes the geographic distribution of V_{S30} and the potential for site conditions to locally amplify ground shaking within a 140-km^2 area along part of the eastern margin of San Francisco Bay, California. The methodology used to prepare the

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resulting map (Holzer et al. 2002) differs from that of earlier maps that included the study area (Borcherdt 1991, Seekins et al. 2000, Wills et al. 2000) in that it both incorporates the impact of the thickness of shallow geologic units on V_{S30} and relies on extensive local measurements of V_S. Comparison of the new map with previously published maps indicates that incorporating these two factors changes the predicted amplification potential of large regions in the study area. In addition, the mean values of V_S of most of the geologic units in the study area tend to fall within a single V_{S30} site class of the National Earthquake Hazards Program (NEHRP) classification (BSSC 2001). If areas that are subject to site amplification are to be mapped for code purposes, the velocities of geologic units may need to be considered in the definition of V_{S30} boundaries of the different site classes in order to take full advantage of geologic maps.

STUDY AREA AND SURFICIAL GEOLOGY

The study area extends from the city of Berkeley southward through the city of Oakland, California, along the coastal plain adjacent to San Francisco Bay. It also includes the communities of Alameda, Emeryville, and Piedmont. Surficial geology, which is generalized from Knudsen et al. (2000) as modified by R. C. Witter and J. M. Sowers (unpublished data), is shown in Figure 1. The area contains five major surficial geologic units in addition to bedrock—artificial fill, younger San Francisco Bay mud, Holocene alluvial fans, Merritt Sand, and Pleistocene alluvial fans. Soil classifications and approximate geologic ages of the surficial geologic units are shown in Table 1.

The study area can be subdivided into three regions based on geology. This subdivision facilitates the computation of V_{S30} because the shallow geologic units within each region are unique to the region and the major variable within a region is unit thickness. The subdivision is intimately related to sea level changes associated with continental glaciation during the Holocene and Pleistocene epochs, and a brief review of this geologic history is instructive before describing the three regions. Particularly important are (1) the last major sea-level decline at the end of the Pleistocene epoch and (2) the ensuing rise of sea level at the beginning of the Holocene epoch, both of which influenced depositional processes in the study area. During the Late Pleistocene sea-level decline, San Francisco Bay was drained of marine water and became dry. Very little deposition occurred in the study area during this low stand of sea level, and local streams incised deep channels as they adjusted to their lower base levels. The principle deposition in the study area was by wind, which created sand dunes that are now preserved as the Merritt Sand. As the continental glaciers melted during the Late Pleistocene, sea level rose and marine waters refilled San Francisco Bay. During this marine transgression, the deposition of the younger bay mud started. Deposition of the mud continued until humans covered it partially with artificial fill. Also as the base level of streams rose and climate changed, alluvial fan deposition resumed in the area east of the area now covered by artificial fill.

For discussion purposes, the three regions are referred to as western, central, and eastern. In the western region, which is the area covered at the surface by artificial fill, the shallowest natural deposit is the younger bay mud. The mud buries the old land surface that was modified by erosion during the Late Pleistocene low sea-level stand. As a result, the thickness of the mud varies from zero along the original shoreline to more

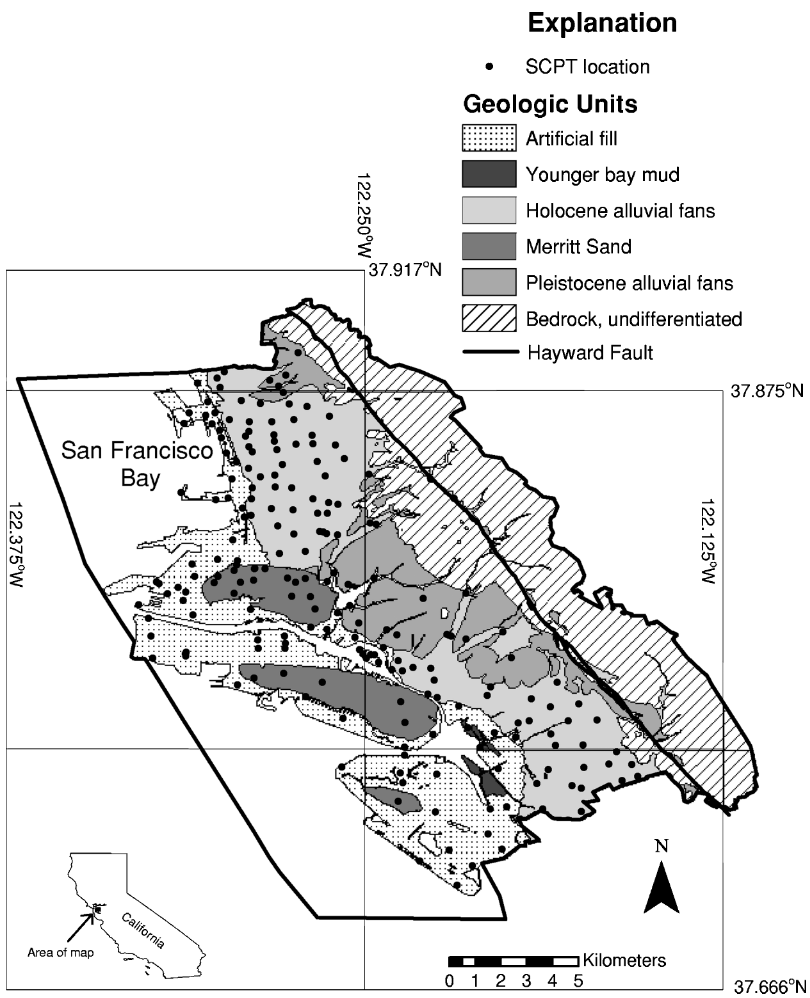

Figure 1. Study area with generalized surficial geology and locations of SCPT soundings. Area includes communities of Alameda, Berkeley, Emeryville, Oakland, and Piedmont, California.

Table 1. Unified Soil Classification (USC) and approximate age of geologic units

Geologic Unit	USC Classification	Geologic age (years before present)
Artificial fill	SM	<150 (Modern)
Younger bay mud	CL	<8,000 (Holocene)
Holocene alluvial fans	CL, SM	<15,000
Merritt Sand	SM	10,000–80,000 (Pleistocene)
Pleistocene alluvial fans	CL, SM	>116,000

than 30 m thick in the study area. The artificial fill that now blankets the mud in this region is mostly sand that was hydraulically placed. The fill in general is not compacted except for a thin surface layer. The thickness of the artificial fill averages about 3 m, but locally exceeds 10 m. In the central region, which is the area between the areas where the surficial unit is either artificial fill or bedrock outcrop, the surficial units are alluvial fan deposits. These fan deposits in the western part of the central region are of Holocene age and are part of a complex of alluvial fans, many of which were active until they were recently stabilized by urbanization. The Holocene alluvial fan deposits bury the Late Pleistocene land surface. The Pleistocene fan deposits are exposed in the eastern part of the central region. The eastern region is the area underlain by bedrock, which ranges from consolidated Cretaceous sediments to Jurassic volcanic rocks crops out (Graymer 2000). Locally within the western and central regions, the Holocene younger bay mud and alluvial fan deposits rest on Merritt Sand. The thickness of the Holocene deposits varies, and locally exceeds 30 m. Ground water is generally encountered at less than 3 m below the land surface in the study area.

The shallow subsurface geology is illustrated by 4 seismic cone penetration test (SCPT) profiles in Figure 2. The geologic units shown in the soundings are the same as those in the surficial geologic mapping as generalized in Figure 1. The profiles include CPT friction ratio and tip resistance and the V_S of each geologic unit. The sounding in Figure 2a was conducted in the central region and penetrated Holocene and Pleistocene alluvial fan deposits. The sounding in Figure 2b was conducted in the eastern part of the central region, and penetrated only Pleistocene alluvial fan deposits. The sounding in Figure 2c penetrated Pleistocene Merritt Sand and underlying Pleistocene alluvial fan deposits. The sounding in Figure 2d was conducted in the western region and penetrated artificial fill, younger bay mud, Pleistocene Merritt Sand, and Pleistocene alluvial fan deposits. By simultaneously measuring penetration resistance and V_S, the major geologic units encountered in a sounding usually could be identified with confidence. For soundings in which unit identification was ambiguous, soil sampling and comparison with adjacent soundings were used to resolve the ambiguity. The SCPT data used in this investigation are available at http://quake.usgs.gov/prepare/cpt/.

SHEAR WAVE VELOCITIES OF GEOLOGIC UNITS

Shear wave velocities of the geologic units are summarized in Table 2. Velocities were measured by the downhole method in each SCPT sounding. The velocities are from Holzer et al. (2005), who examined the statistical distribution and depth dependence of V_S of the geologic units. The values of V_S in Table 2 were determined by two approaches. In the first approach, the V_S of each 2-m-depth interval in a SCPT sounding was computed and assigned to the appropriate geologic unit; then an average for each geologic unit was computed from these values. The 2-m interval was the depth increment over which velocity typically was measured in each sounding. In the second approach, the average V_S of the entire geologic unit penetrated in a given sounding was calculated, and then these values were averaged. The two velocities, respectively, are referred to here as the 2-m-interval and unit velocities. Mean values of slowness, which is the inverse of velocity, were also computed. Average slowness is more appropriate for computing V_{S30} because it emphasizes the lower V_S values, which have the greater im-

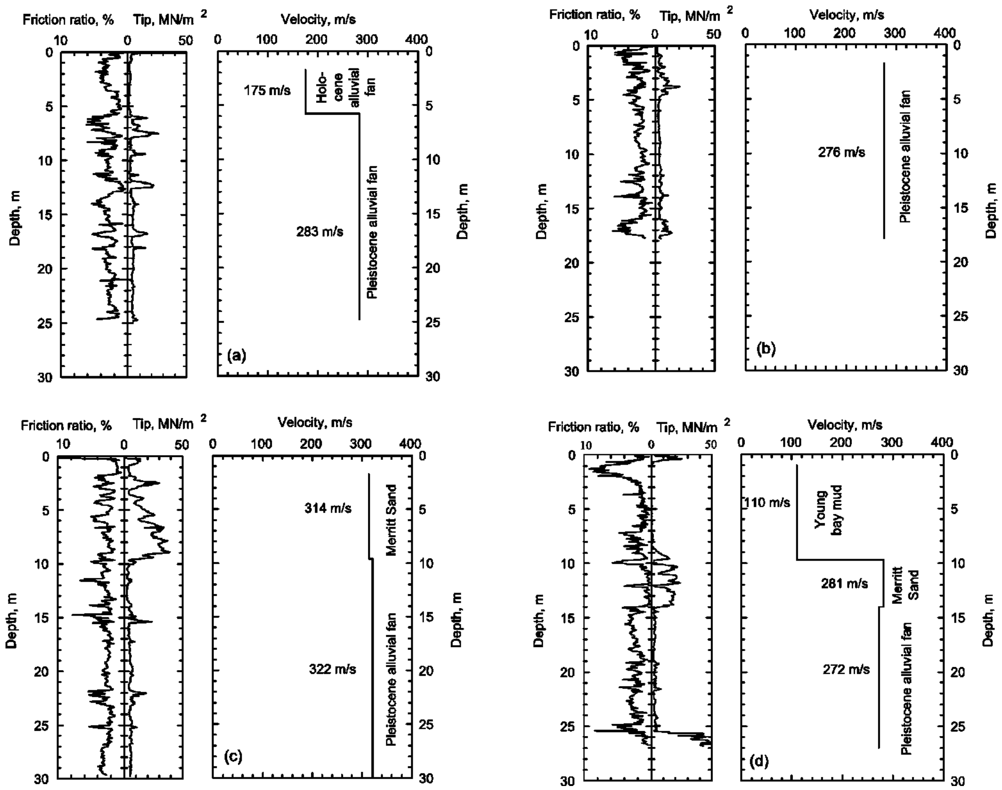

Figure 2. Selected SCPT sounding profiles of friction ratio and tip resistance with V_S of geologic units: (a) OAK099, Holocene alluvial fans overlying Pleistocene alluvial fans; (b) OAK070, Pleistocene alluvial fans; (c) OAK007, Merritt Sand overlying Pleistocene alluvial fans; and (d) OAK041, artificial fill, younger bay mud, Merritt Sand, and Pleistocene alluvial fans (from Holzer et al. 2005).

pact on estimating V_{S30} (Brown et al. 2002). To facilitate velocity comparisons, the inverse of the mean slowness is reported in Table 2. The map of NEHRP site classes to be described here is based on the average 2-m-interval slowness. Use of the 2-m-interval slowness permits incorporation of vertical gradients of velocity (slowness) in the velocity model for units where gradients are significant.

Although the V_S of three of the geologic units—the Merritt Sand and Holocene and Pleistocene alluvial fans—is approximately constant with depth, the V_S of the younger bay mud increases markedly with depth (Figure 3). The V_S of the artificial fill is not included in Figure 3 because it is less than 4.5 m thick in most of the study area. Linear regression of the 2-m-interval V_S for younger bay mud with respect to depth (z) yields $V_S=3.99z+75.2$; the least-squares fit for slowness (V_S^{-1}) is $V_S^{-1}=-0.000288z+0.0120$. Holzer et al. (2005) conclude that the depth dependence of the younger bay mud is the result of consolidation caused by the increasing weight of the overburden. In

Table 2. V_S of geologic units

V_S (m/s)	Fill (0–1.75 m)	Fill (>1.75 m)	Younger bay mud	Holocene alluvial fans	Pleistocene alluvial fans	Merritt Sand
2-m interval V_S						
Arithmetic Mean	184	159	128	224	330	325
(Average Slowness)$^{-1}$	170	152	118	214	312	311
Entire geologic unit V_S						
Arithmetic Mean	184	163	109	209	319	332
(Average Slowness)$^{-1}$	170	153	106	204	313	324

addition, Holzer et al. (2005) show that placement of artificial fills on the younger bay mud has caused consolidation of the mud and increased its V_S. The increase is proportional to fill thickness.

NEHRP V_{S30} SITE CLASSIFICATION

Velocity boundaries of the NEHRP site classification for estimating the capability of shallow soil and rock to locally amplify strong ground motion are summarized in Table 3. This classification is widely used in the United States and has been incorporated into

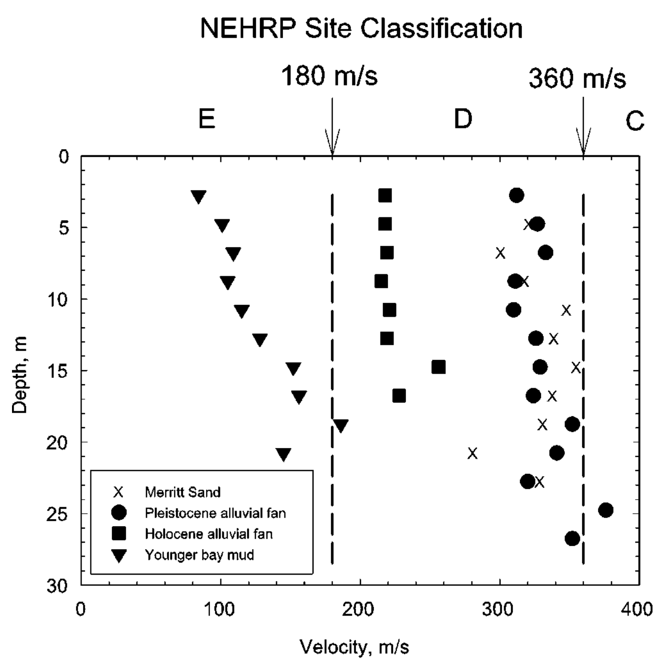

Figure 3. Observed shear-wave velocity of geologic units and NEHRP site classes with V_{S30} boundaries (modified from Holzer et al. 2005).

Table 3. NEHRP site classes, adapted from BSSC (2001) based on V_{S30}

Site Class	Soil Profile Name	V_{S30} (m/s) Minimum	Maximum
A	Hard rock	>1500	
B	Rock	>760	1500
C	Very dense soil and soft rock	>360	760
D	Stiff soil	180	360
E	Soft soil		<180

many building codes. Dobry et al. (2000) describe the history of the development of the classification, which was first published in the 1994 NEHRP provisions (BSSC 1995). The NEHRP classification of a site is based primarily on a time-averaged shear-wave velocity to a depth of 30 m (V_{S30}), which is the ratio of 30 m to the travel time of a vertically propagating shear wave between a depth of 30 m and the land surface (Dobry et al. 2000). Velocity profiles may be measured directly or inferred from correlations of shear wave velocity with penetration resistance or undrained shear strength. For the seismic design of a code-compliant structure, the V_{S30} beneath the structure determines the appropriate short- and mid-period amplification factors—which are not shown here—to be applied to modify the reference earthquake spectra (e.g., Dobry et al. 2000). It should be noted that a type E classification is also assigned to sites where soft clays (defined on the basis of plasticity, moisture content, and undrained shear strength) are thicker than 3 m. For the purpose here, however, site class assignments will be based only on V_{S30}. The emphasis here on using only V_{S30} to classify a site is also important because all of the area classified as E and some of the area classified as D is actually NEHRP Site Class F because it is underlain by liquefiable artificial fill (Holzer et al. 2002).

MAP OF NEHRP V_{S30} SITE CLASSES

Figure 4 is the new map of NEHRP V_{S30} site classes within the study area. The map portrays the geographic distribution of V_{S30} and relies on the NEHRP site classification to categorize V_{S30} values (Table 3).

The site class map was prepared by creating maps of thickness of Holocene sediment and artificial fill and then using average velocities of these units and underlying Pleistocene sediment to estimate V_{S30}. The map of surficial geology was used to identify the geologic unit at the land surface. In areas that were mapped as either Pleistocene sediment or bedrock, the surface unit was assumed to be 30 m thick. Actual preparation of the NEHRP V_{S30} site classification map was conducted in three steps.

In step one, the depth to the base of the Holocene deposits was determined in the SCPT soundings and commercial borings provided by the California Geological Survey and the Port of Oakland. These depth values were then contoured (Figure 5a). Contouring was done manually because, as was previously noted, many of the streams in the region had eroded valleys into the underlying Pleistocene deposits when base levels fell in response to sea level declines during the last glaciations. These valleys are now filled

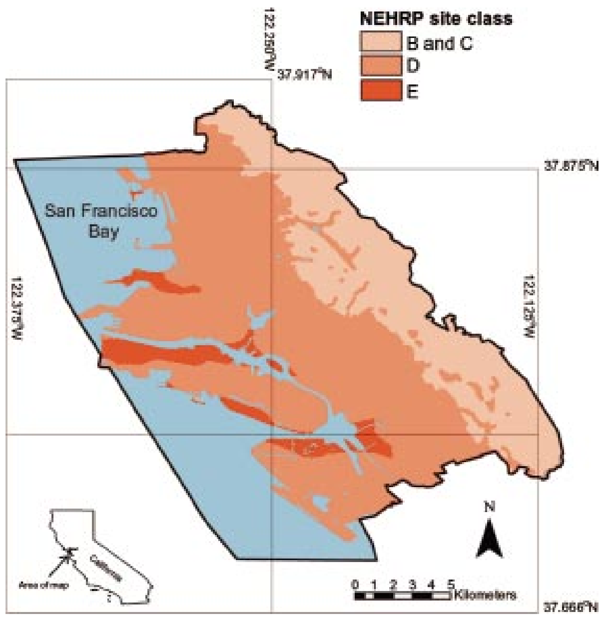

Figure 4. Map of NEHRP V_{S30} site classes.

with the Holocene deposits. Manual contouring helped maintain the integrity of the resulting buried valleys. In addition to mapping the base of the Holocene deposits, a map of the thickness of artificial fill was prepared (Figure 5b).

In step two, the maps of the base of the Holocene and thickness of artificial fill were discretized with a 50-m grid. The grid was then subdivided into the three geologic regions previously discussed. The subdivision was necessary in order to assign the appropriate V_S values to the geologic units. Holocene sediment consists of artificial fill and younger bay mud in the western region and alluvial fan deposits in the central region.

In step three, values of V_S, based on mean 2-m-interval slowness values, were assigned to each layer at each node in the grid based on the region in which the node was located. V_{S30} was then computed at each node in the grid based on the estimated travel time of a vertically propagating shear wave through all layers in the uppermost 30 m. The velocities as computed from slowness are compiled in Table 4. Because V_S (slowness) of all geologic units except for younger bay mud is approximately constant with depth, constant values of slowness for all but the younger bay mud were used to estimate V_{S30}. To compute the travel time through the younger bay mud, the linear regression for slowness was integrated over the depth interval of the mud. Slowness values of the younger bay mud were adjusted (increased) to take into account the effect of consolidation caused by the weight of the overlying artificial fill. The adjustment was based on the thickness of the artificial fill and the ratio of the buoyant unit weights of the fill and younger bay mud, 1.99 (see Holzer et al. 2005). This effect of the artificial fill on the V_S of the younger bay mud is described by Holzer et al. (2005).

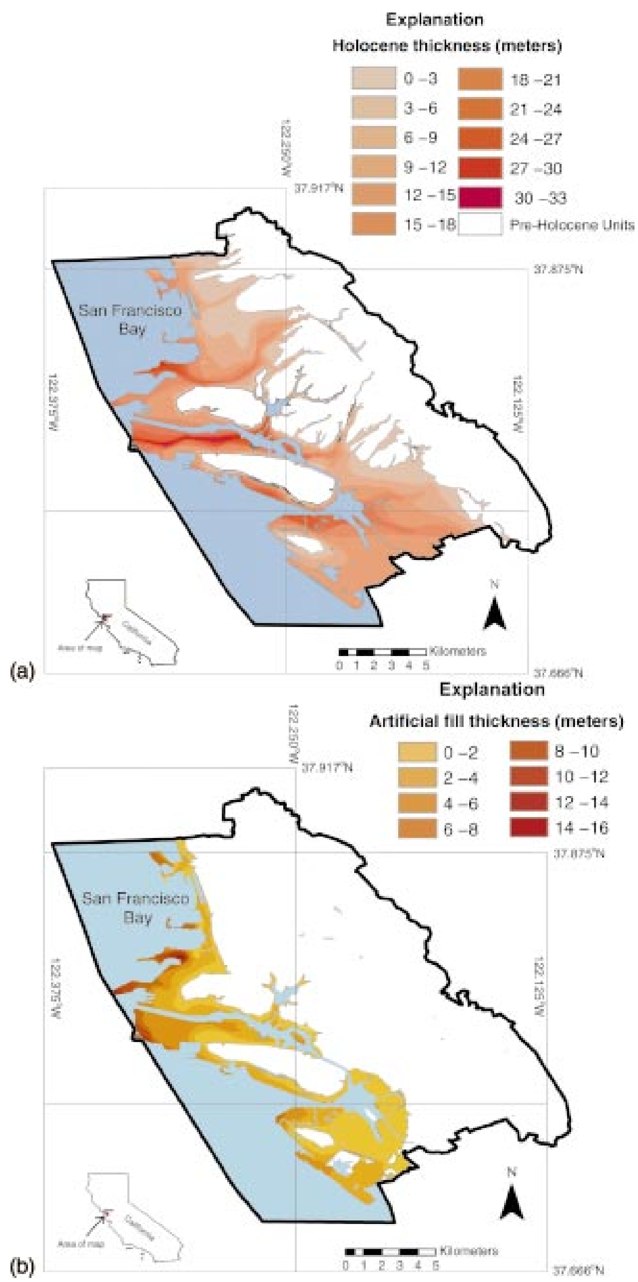

Figure 5. (a) Map of thickness of Holocene deposits, and (b) map of thickness of artificial fill.

Table 4. V_S values (from slowness) used to compute V_{S30} for map of NEHRP site classes in Figure 4

	V_S (m/s)			
	Western region	Central region	Eastern region	Merritt Sand outcrop area
Fill, upper 1.75 m	170	NA	NA	NA
Fill, >1.75 m	152	NA	NA	NA
Holocene deposits	Linear[1]	214	NA	NA
Pleistocene deposits	311	312	NA	311
Bedrock	NA[2]	NA	>360	NA

[1] Regression for slowness of younger bay mud, $(V_S)^{-1} = -0.000288z + 0.0120$, was used to compute travel time through layer
[2] NA indicates layer not present in region

Although assignment of V_S values to geologic units may seem straightforward, two aspects of the assignments shown in Table 4 warrant additional discussion. First, Holzer et al. (2005) reported that the mean V_S of the upper 1.75 m of the artificial fill typically was higher, 170 m/s, than the mean V_S measured below this depth, 152 m/s. The higher V_S of the uppermost fill is caused by compaction during its placement. Accordingly, the velocity model for the fill layer included a 1.75-m-thick surficial layer with a V_S of 170 m/s. Second, the V_S of the younger bay mud reported in Table 4 is for the upper or soft member, which is the predominant component of the younger bay mud in the study area (see Holzer et al. 2005). The younger bay mud locally includes a semi-consolidated lower member that has a V_S that is higher than that of the rest of the unit. The lower member is not geographically continuous in the study area and was observed in only a few soundings. Inclusion of V_S data from the lower member would raise the average velocity of the younger bay mud by about 10 percent (Holzer et al. 2005).

DISCUSSION

Three aspects of the new map of site classification merit further discussion here. First, the map can be compared to previously published smaller-scale maps that include the study area, but that were prepared with different methodologies. Second, compilation of the velocity data by geologic unit provides an opportunity to evaluate the NEHRP V_{S30} boundaries in a geologic context rather than the soil texture context as they were primarily defined originally. And third, despite the extensive measurements of velocities of geologic units in the study area, assignment of velocities to the geologic units involves judgment. The implications for mapping of alternative velocity assignments can be evaluated.

COMPARISON WITH OTHER MAPS

NEHRP site classifications in the study area are included in smaller scale maps published by Wills et al. (2000) and Seekins et al. (2000). These other two maps, which rely on estimates of V_{S30}, shared a common approach: the geographic distribution of V_{S30}

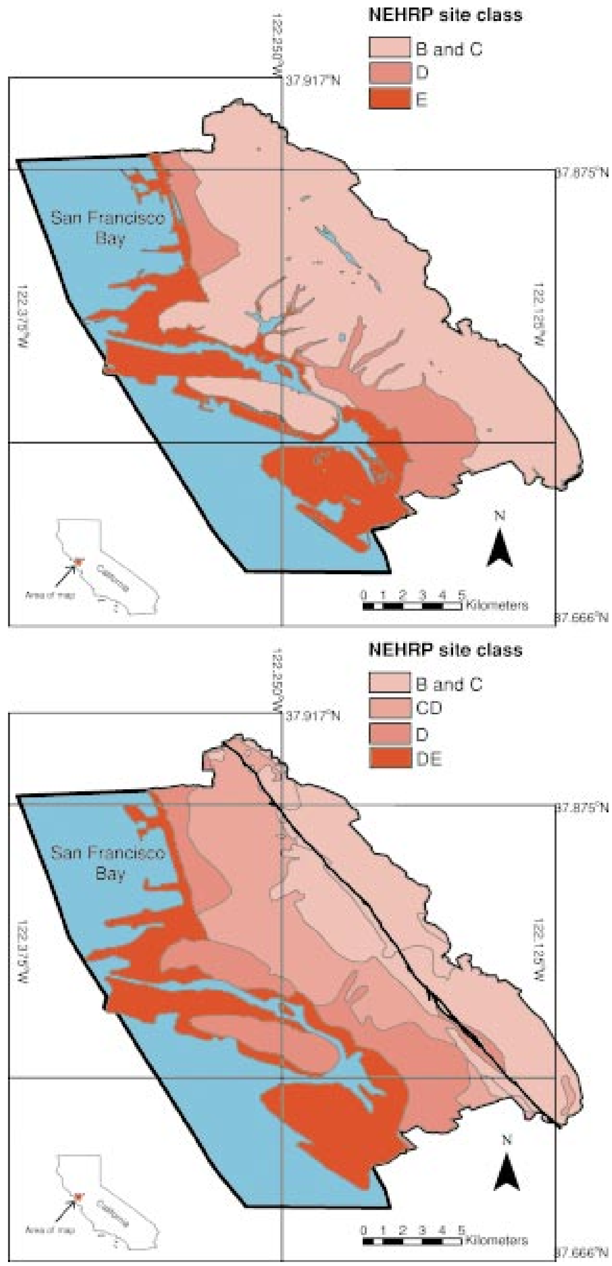

Figure 6. (a) Map of NEHRP site classes by Seekins et al. (2000), and (b) map of NEHRP site classes with modifications by Wills et al. (2000).

was based on geologic maps. These maps of site classification, however, cover different areas at dissimilar scales and used different velocity data. Wills et al. (2000) mapped all of the State of California; Seekins et al. (2000) mapped only the San Francisco Bay region. The former map was based on 1:250,000 scale geologic maps; the latter map was based on 1:125,000 scale maps that portrayed physical properties of geologic materials (Wentworth 1997). Wills et al. (2000) used a state-wide correlation of V_{S30} with mapped geologic units (Wills and Silva 1998); Seekins et al. (2000) relied on a regional compilation of V_S from the Bay Area to assign values of V_{S30} to surficial units. Neither map explicitly considered the thickness of mapped surficial geologic units.

These two maps are shown in Figure 6 and can be compared with the new map in Figure 4. Differences between the precise locations of the boundaries of the site classes are to be expected because the maps are based on different geologic maps. Usually, the resolution of geologic boundaries decreases as the scale of the mapping gets smaller. The new map presumably provides the greatest resolution of the three maps because it is based on 1:24,000 scale geologic mapping. Two differences between the published maps and the new map, however, are significant: (1) the published maps designate all of the western area as Site Class E (DE for Wills et al. [2000]), whereas the new map designates only part of the area as Site Class E; and (2) the published maps designate most of the central area as Site Class C (CD for Wills et al. [2000]), whereas the new map designates the areas as mostly Site Class D. The implication of classifying a larger area as Site Class E is that a larger area will be subject to the greatest amplification potential, at least at lower levels of shaking; the implication of classifying a large area as Site Class C is that it predicts a lower level of amplification in much of the study area because most of this area is actually Site Class D.

The differences between the two published maps and the new map illustrate the importance of including thickness of shallow geologic units and local measurements of V_S. The decrease in the area of Site Class E is attributable to the thinness of the younger bay mud in the western region outside the buried valleys. The mud is only thick enough to cause V_{S30} to be less than 180 m/s (Site Class E) in areas where it fills the buried valleys; between valleys the mud is not thick enough to cause V_{S30} to be less than 180 m/s. The smaller area classified as C (and larger area classified as D) in the new map is caused by the lower values of V_S measured in the Pleistocene alluvial fan and Merritt Sand deposits in the study area (Figure 3). The average V_S of these geologic units is less than 360 m/s, the upper boundary of Site Class D.

NEHRP SITE CLASS BOUNDARIES

Observed velocities of the geologic units in the study area are compared to the NEHRP V_{S30} boundaries in Figure 3. Although much of the area is classified as Class D ($180<V_{S30}<360$ m/s), the V_S of geologic units underlying this area have a broad range with little overlap. The V_S of Holocene alluvial fan sediment is slightly greater than the lower NEHRP boundary, 180 m/s, and the V_S of the Pleistocene Merritt Sand and alluvial fan sediments are slightly less than the upper boundary, 360 m/s. These units would be more readily distinguished from each other by an intermediate V_{S30} boundary. The impact of an intermediate boundary such as 270-m/s on the site classification map is substantial (Figure 7). For illustrative purposes, two new site classes, D_1 and D_2, with

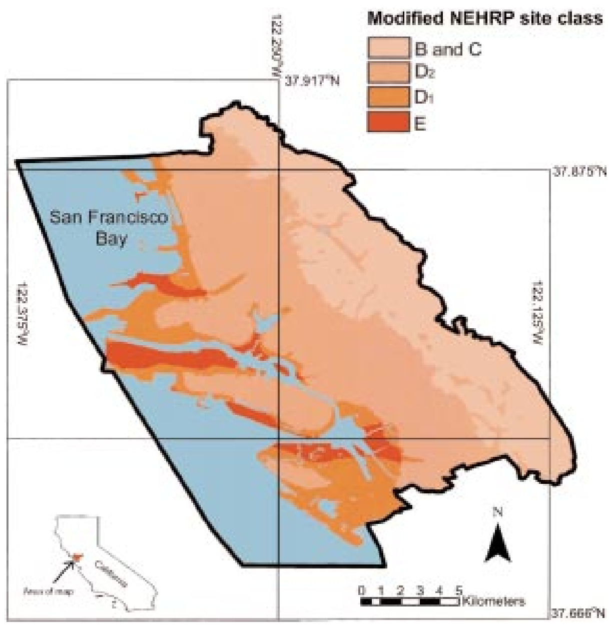

Figure 7. Map of NEHRP V_{S30} site classes with Site Class D subdivided into classes D_1 (180–270 m/s) and D_2 (270–360 m/s).

V_{S30} that range from 180 to 270 m/s and from >270 to 360 m/s, respectively, are mapped in Figure 7. Comparison of the new map with the NEHRP site classification map (Figure 4) indicates that most of the area classified as Class D area is Class D_2. This implies that the amplification potential in the area mapped as Class D is generally lower than is indicated by its NEHRP classification (see Borcherdt 1994).

The map in Figure 7 suggests a potential shortcoming in the NEHRP V_{S30} site class boundaries when they are used for mapping purposes in the greater Oakland region. It derives from the fact that geology was not considered in the definition of the NEHRP V_{S30} boundaries. The shortcoming previously was recognized on a statewide basis in California by Wills et al. (2000), who proposed a 270 m/s boundary to identify and separate site classes DE and CD (see Wills et al. 2000, Table 4). The situation arises because soil texture was the primary consideration that influenced the choice of the NEHRP V_{S30} boundaries (Borcherdt 1994). Geologic considerations were only indirectly incorporated by including penetration resistance and undrained shear strength as factors in site classification.

If mapping of NEHRP site classification is to be based on geologic maps, the experience of the writers and that of Wills et al. (2000) suggests that velocity distributions of geologic units may need to be considered when the definition of NEHRP site classes is revised in the future. Recent endeavors to characterize seismic shaking hazard in California support this. Following the 1989 Loma Prieta, California, earthquake, California passed the 1990 Seismic Hazards Mapping Act, which mandated the mapping of zones

Table 5. V_S values (from slowness) used to compute V_{S30} for map of NEHRP site classes in Figure 8

	V_S (m/s)			
	Western region	Central region	Eastern region	Merritt Sand outcrop area
Fill, upper 1.75 m	133	NA	NA	NA
Fill, >1.75 m	125	NA	NA	NA
Holocene deposits	Linear[1]	174	NA	NA
Pleistocene deposits	258	250	NA	258
Bedrock	NA[2]	NA	>360	NA

[1] Modified regression for slowness of younger bay mud, $(V_S)^{-1} = -0.000288z + 0.0134$, was used to compute travel time through layer
[2] NA indicates layer not present in region

subject to strong ground shaking in addition to mapping potential liquefaction and landslides zones. The primary shaking hazard map published by the state is by Petersen et al. (1996). One feature of the map is that it shows areas where high levels of shaking are to be expected near faults. If areas subject to site amplification are to be mapped and assigned to NEHRP site class as well, the V_{S30} boundaries need to distinguish between the observed velocity distributions of geologic units. If the boundaries do not consider this nuance, the use of geologic maps to predict geographic distributions of site classes will be partially compromised. As previously noted, consistency with geologic units was not the primary original intent of the NEHRP site classification.

The recent findings of Stewart et al. (2003), who reported that incorporating detailed surface geology at soil sites provided an effective means of categorizing spectral amplification factors at small periods, provides further justification for the use of geologic considerations to define site classes. They found that including geologic age of Quaternary (Holocene and Pleistocene) units, depositional environment, and soil texture in empirical relations to predict spectral amplification factors reduced the resulting dispersion.

SENSITIVITY TO SHEAR WAVE VELOCITY

Because the assignment of V_S values to geologic units during the preparation of the new map involves some judgment, the sensitivity of the NEHRP V_{S30} site classification map to alternative velocity assignments is worth exploring. A simple test is to include statistical variability. Although not robust, one approach is simply to compute V_{S30} values using V_S (actually slowness) values for geologic units that are one standard deviation less than mean V_S values (Table 5). The resulting map, which overemphasizes the potential for site amplification, is shown in Figure 8. The primary impact is to increase the size of the area underlain by Site Class E.

The assignment of V_S values to geologic units in the study area was most challenging in the western region. In particular, the SCPT investigation of Pleistocene sediment buried beneath Holocene sediment in this region revealed that two types of deposits were present, Merritt Sand and fine-grained sediment. In the vicinity of the outcrops of Mer-

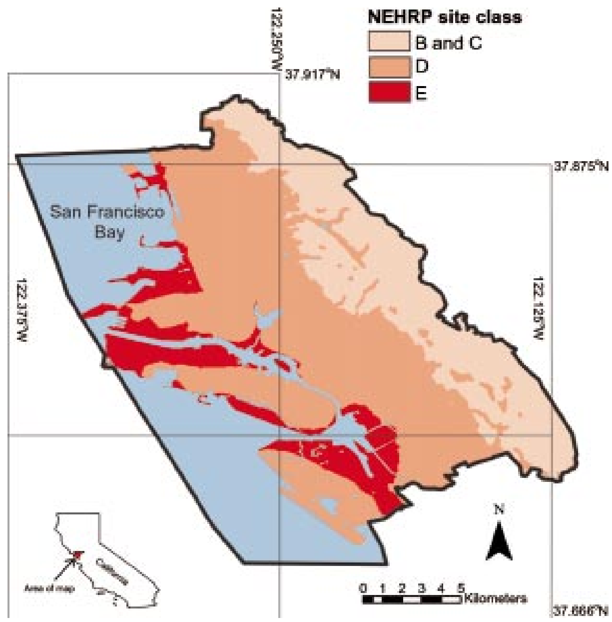

Figure 8. Map of NEHRP site classes with V_{S30} estimates based on one sigma V_S values.

ritt Sand in Oakland and Alameda, the Merritt Sand typically underlies Holocene sediment. However, away from its areas of outcrop, the Merritt Sand typically is absent or very thin in the upper 30 m. In areas distant from the Merritt Sand outcrops, many soundings penetrated substantial thicknesses of Pleistocene sediment that was fine-grained and slow ($V_S \approx 241$ m/s). The writers interpret this sediment to be a combination of an older bay mud—informally known as the Yerba Buena mud member of the San Antonio Formation (Sloan 1992)—and distal Pleistocene alluvial fan deposits, an interpretation reached earlier by McGann et al. (2002). These two fine-grained facies could not be distinguished from each other everywhere, but fortunately for the purpose here their velocities are similar. Figure 9 shows the impact on the map of assigning a V_S of 241 m/s to the buried Pleistocene deposits in the western region. The predicted NEHRP site class in Figure 4, which assumes a Pleistocene V_S of 311 m/s in the western region, presumably is reliable near the areas of Merritt Sand outcrop. However, the lack of regional continuity of the Merritt Sand in the subsurface implies that the assumption of a V_S of 311 m/s may be inappropriate regionally for the Pleistocene sediments, particularly in areas distant from outcrops of the Merritt Sand. In these parts of the western region, a V_S of 241 m/s may be appropriate. Unfortunately, better resolution of the geology in the lower part of the upper 30 m is required than is possible with the current suite of soundings and borings.

The maps in Figures 8 and 9 are very similar. This similarity results from assignment of comparable V_S values to the Pleistocene deposits in the western region. In Figure 8, the V_S is 258 m/s; in Figure 9 the V_S is 241 m/s. Both maps when compared to the map

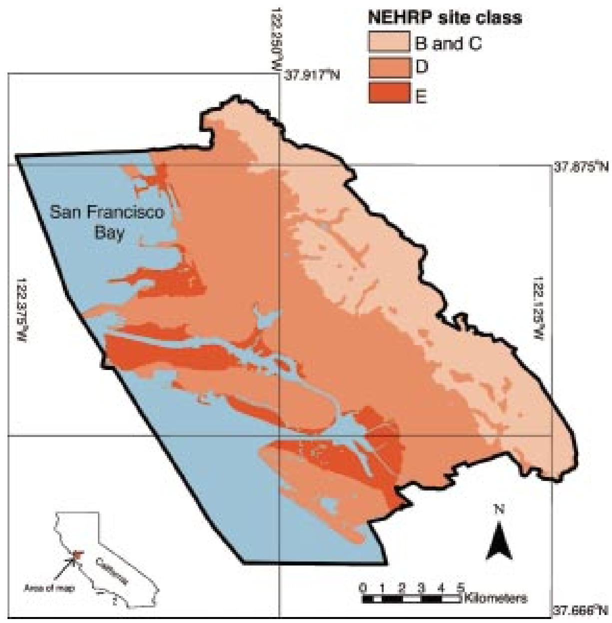

Figure 9. Map of NEHRP site classes in which average V_S of Pleistocene deposits in western region is assumed to be 241 m/s.

in Figure 4 portray larger areas of Site Class E at the expense of the area classified as Site Class D. The areas classified as E in Figures 8 and 9 fortuitously compare more favorably with areas mapped as Site Class E by Wills et al. (2000) and Seekins et al. (2000) than does the area classified as E in Figure 4.

CONCLUSIONS

Consideration of thickness of shallow geologic units and locally measured values of V_S leads to a significantly different map than previously published regional maps that included the study area but that did not consider thickness and relied on regional compilations of velocity data. In the new map, the size of areas classified as E and D is substantially decreased and increased, respectively, by including these two factors. The decrease in area of Site Class E is caused by taking thickness of younger bay mud into account. The increase in area of Site Class D is caused by using locally measured values of V_S, which are lower than estimates from regional compilations. Although much of the area in the new map is classified as NEHRP Class D, velocities of the geologic deposits within this area are either near the upper or lower V_{S30} boundary of Class D. If NEHRP site classes are to be mapped based on geologic maps, V_S distributions of geologic units may need to be considered in the definition of V_{S30} boundaries of NEHRP site classes.

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REFERENCES

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.

Borcherdt, R. D., 1991. On the observation, characterization, and predictive GIS mapping of strong ground shaking for seismic zonation—A case history for the San Francisco Bay region, *Proceedings, Pacific Conference on Earthquake Engineering, Auckland, New Zealand*, pp. 1–24.

Borcherdt, R. D., 1994. Estimates of site-dependent response spectra for design (methodology and justification), *Earthquake Spectra* **10** (4), 617–653.

Borcherdt, R. D., 2002. Empirical evidence for site coefficients in building code provisions, *Earthquake Spectra* **18** (2), 189–217.

Brown, L. T., Boore, D. M., and Stokoe, II, K. H., 2002. Comparison of shear-wave slowness profiles at 10 strong-motion sites from noninvasive SASW measurements and measurements made in boreholes, *Bull. Seismol. Soc. Am.* **92** (8), 3116–3133.

Building Seismic Safety Council (BSSC), 1995. *1994 Edition, NEHRP Recommended Provisions for Seismic Regulations for New Buildings, FEMA 222A/223A*, Vol. 1 (Provisions) and Vol. 2 (Commentary), developed for the Federal Emergency Management Agency, Washington, D.C.

Building Seismic Safety Council (BSSC), 2001. *2000 Edition, NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures, FEMA-368*, Part 1 (Provisions): developed for the Federal Emergency Management Agency, Washington, D.C.

Dobry, R., Borcherdt, R. D., Crouse, C. B., Idriss, I. M., Joyner, W. B., Martin, G. R., Power, M. S., Rinne, E. E., and Seed, R. B., 2000. New site coefficients and site classification system used in recent building code provisions, *Earthquake Spectra* **16** (1), 41–68.

Graymer, R. W., 2000. Geologic map and map database of the Oakland Metropolitan Area, Alameda, Contra Costa, and San Francisco Counties, California, *U.S. Geological Survey Miscellaneous Field Study Map 2342*.

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

Holzer, T. L., Bennett, M. J., Noce, T. E., Padovani, A. C., and Tinsley, J. C., III, 2002. Liquefaction hazard and shaking amplification maps of Alameda, Berkeley, Emeryville, Oakland, and Piedmont: A digital database, *U.S. Geol. Surv. Open-File Rep. 02–296* (http://geopubs.wr.usgs.gov/open-file/of02-296/).

Holzer, T. L., Bennett, M. J., Noce, T. E., and Tinsley, III, J. C., 2005. Shear-wave velocity of surficial geologic sediments in Northern California: Statistical distributions and depth dependence, *Earthquake Spectra* **21** (1), 161–177.

International Council of Building Officials (ICBO), 2000. *International Building Code*, Falls Church, VA.

Joyner, W. B., and Boore, D. M., 1988. Measurement, characterization, and prediction of strong ground motion, *Recent Advances in Ground-Motion Evaluation*, edited by J. L. Von Thun, American Society of Civil Engineers, New York, pp. 43–102.

Knudsen, K. L., Sowers, J. M., Witter, R. C., Wentworth, C. M., Helley, E. J., Nicholson, R. S., Wright, H. M., and Brown, K. H., 2000. Preliminary maps of quaternary deposits and liquefaction susceptibility, nine-county San Francisco Bay region, California: A digital database, *Open-File Rep./U.S. Geol. Surv.* (http://geopubs.wr.usgs.gov/open-file/of00-444/).

McGann, M., Sloan, D., and Wan, E., 2002. Biostratigraphy beneath central San Francisco Bay along the San Francisco–Oakland Bay Bridge transect, in *Crustal Structure of the Coastal San Francisco Bay Region, California*, edited by T. Parson, *U.S. Geol. Surv. Prof. Pap. 1658*, pp. 11–28.

Petersen, M. D., Bryant, W. A., Cramer, C. H., Cao, T., Reichle, M., Frankel, A. D., Lienkaemper, J. J., McCrory, P. A., and Schwartz, D. P., 1996. Probabilistic seismic hazard assessment for the state of California, *California Geological Survey Open-File Report 96–706*.

Seekins, L. C., Boatwright, J., and Fumal, T., 2000. Soil Type and Shaking Hazard in the San Francisco Bay Area, U.S. Geological Survey: http://quake.wr.usgs.gov/hazprep/soil_type/.

Sloan, D., 1992. The Yerba Buena mud, record of the last interglacial predecessor of San Francisco Bay, California, *Geol. Soc. Am. Bull.* **104** (6), 716–727.

Stewart, J. P., Liu, A. H., and Choi, Y., 2003. Amplification factors for spectral accelerations in tectonically active regions, *Bull. Seismol. Soc. Am.* **93** (1), 332–352.

Wentworth, C. M., 1997. General distribution of geologic materials in the San Francisco Bay region, California: A digital map database, *U.S. Geol. Surv. Open-File Rep. 97–744* (http://geopubs.wr.usgs.gov/open-file/of97-744).

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 Silva, W., 1998. Shear-wave velocity characteristics of geologic units in California, *Earthquake Spectra* **14** (3), 533–556.

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