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ON THE CORRELATION OF SITE CLASSIFICATIONS ESTIMATED FROM SURFACE GEOLOGY, TOPOGRAPHIC SLOPE, AND SHEAR-WAVE VELOCITY MEASUREMENTS

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ABSTRACT

Ground motion amplification due to soft soil site condition can significantly increase the hazard level or shaking damage at a location. The current standard practice for estimating site amplification is to characterize site condition in terms of the average shear-wave velocity of the top 30 meters of soil layer (Vs30). It is preferable to measure Vs30 using various seismic or geotechnical techniques. However this approach is only practical for site-specific hazard or earthquake engineering analysis. For regional earthquake hazard or risk studies, we need to rely on cost effective approaches to map local site conditions. Such approaches include using surfacial geological maps, geomorphologic maps, high resolution topographic data, or the combination of them.

In this study we compare site condition maps developed from high resolution geologic maps and high resolution topographic data to examine the similarities or differences in site conditions estimated from the two different approaches. Our analysis shows that sites that are classified as National Earthquake Hazard Reduction Program (NEHRP) type D or E from surfacial geologic data are predominantly on slow topographic slopes and can be classified as type D or softer soil based on topographic data. Exposed bedrock sites on high resolution geological maps generally have steeper slope, thus both the geologic approach and topographic approach would lead to firm or hard rock site class (B and C type). However sites classified as type C or B from surface geology (old Quaternary coarse sediments, tertiary sediments etc) have a widespread slope distribution. Slope data cannot distinguish type B sites from type C or CD sites. Moreover, topographic data do not have enough resolution to distinguish sites classified as type E from type D sites. The limitation in the topographic slope approach and the limitation previously noticed in the geological approach require that we should use multi-approaches, whenever possible, to reduce the uncertainty in site classification when developing regional seismic condition maps. The close correlation between the estimated site classes from geologic and topographic methods for some of the most important site classes (e.g. type D) indicates that the two approaches can be used together and complement each other to develop more reliable regional seismic site condition maps.

Introduction

The recognition of the importance of ground motion amplification due to site condition has led to the development of systematic approaches to develop seismic site condition maps (e.g.

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Park and Elrick 1998; Wills et al. 2000; Wald and Allen 2007; Allen and Wald 2009). Based on empirical studies by Borcherdt and Glassmoyer (1994), Borcherdt (1994) recommended the average shear wave velocity in the top 30 m of soil layer (Vs30) as a means of classifying site for building codes. Similar site categories were selected for the NEHRP seismic design provisions for new buildings (Martin 1994). It now becomes the standard practice to use Vs30 for classify site conditions for ground motion amplification consideration. Vs30 can be obtained using various geotechnical approaches such as borehole measurements and shallow sub-surface seismic surveys. However such approaches are generally cost-prohibitive and cannot be used to develop site classification maps over a large area. Vs30 has been correlated with surface geology (Fumal and Tinsley 1985; Park and Elrick 1998; Wills and Silva (1998), Wills et al. 2000) and such correlation has been used to generate regional or state wide site classification maps using geological maps (e.g. Wills et al. 2000). This method is efficient when digitized geological maps are available. However it has limitations. For example the mapping between geologic units and shear-wave velocity can have large uncertainties. The same geological unit can have a wide range of Vs30, resulting in a variation in amplification by a factor of two (Wald and Mori, 2000). The main reason for the large uncertainty in the correlation is because geological units, especially young geological units that can cause significant amplification, are generally grouped according to their age and depositional environment, rather than on physical properties such as density, grain size, and thickness of the formation that determine Vs30. Digitizing and interpreting large scale geologic maps covering a large region (a state or a country) can also be cost-prohibitive. Wald & Allen (2007) has recently developed a method to use topographic slope to estimate Vs30. This method seems very simple and cost-effective since topographic data are freely available and it can be used to develop site condition maps covering large areas quickly. However whether this method can be used to reliably estimate site conditions is still unknown.

In this study we compare site condition maps developed from high resolution geologic maps and high resolution topographic data to examine the similarities or differences in site conditions estimated from the two different approaches. The main objective of the study is to evaluate the strength and limitations of each approach and propose a new approach to develop more reliable site condition maps. We evaluate our results by comparing site condition maps developed from these different methods with available Vs30 data.

Comparison of Site Classification Maps from Surface Geology and Topography in Active Tectonic Region

Several studies have been carried out to create site classification maps using surface geological information from geological maps (Fumal and Tinsley 1985; Park and Elrick 1998; Wills and Silva 1998; Wills et al. 2000; Wills and Clahan 2006). These studies grouped geological units based on their age, lithology, and/or grain size, and assigned a soil classes (NEHRP site classes) to each group based on the available mean shear wave velocities (Vs30) of the unit. Following the correlation table between the geological units and NEHRP soil classes and measured Vs30 established by Wills et al (2000), we created a site classification map in California using the 1:250,000 geological map of California (California Division of Mines and Geology 1958-1990).

To create a site classification map in the same region from topographic slope, we follow the procedure of Wald and Allen (2007) and used the high resolution (3 arc-second) SRTM global topographic data. In order to use the relationship between topographic slope and Vs30 established by Allen and Wald (2009), the 3 arc-second topographic data are re-sampled to get the 9 arc-second data.

To compare the two results, we first rasterized the site classification map from geology with a uniform cell size of about 200 meters. Then the maximum slope at each cell is calculated using the 9 second topographic data. Figure 1 shows the distribution of slope for each class of soil type inferred from geology. The red vertical lines in each histogram correspond to the slope boundary between different NEHRP soil classes. The slope range for classes D and E are grouped together in the histograms since the vertical resolution (elevation) of the global topographic data is not sufficient to resolve slopes lower than 1e-3, which correspond to class E site. Table 1 lists the percentage distribution of the slope based soil types for each given geology-based soil type. Figure 1 shows that cells identified as type D or E from geologic data are predominately D type sites from slope data. Nearly 97% of the D and E type cells in the geology-based site map are correlated with the D type site condition determined from slope data (Table 1), indicating that areas of soft soil site identified from geological data can be inferred from slope data quite well.

For type C sites in the geology based map, about 59% of the cells has a Vs30 in the range of CD to BC (from 360 m/s to 760 m/s) based on slope data, of which only 18% close to the median Vs30 for type C. Of the remaining 41% of the class C cells in the geology based map, one half have steep slope with a calculated Vs30 corresponding to type B to harder, and the other half have a calculated Vs30 corresponding to type D.

Table 1. Percentage distribution of slope based soil types for each soil type from geology in California. The sum in each column equals 100%.

Slope based Type	Soil Type from geology (in %)		
	B	C	D
B (>760)	41	20	0
BC (620-760)	16	13	0
C (490-620)	19	18	0
CD (360 – 490)	19	28	3
D (< 360)	5	21	97

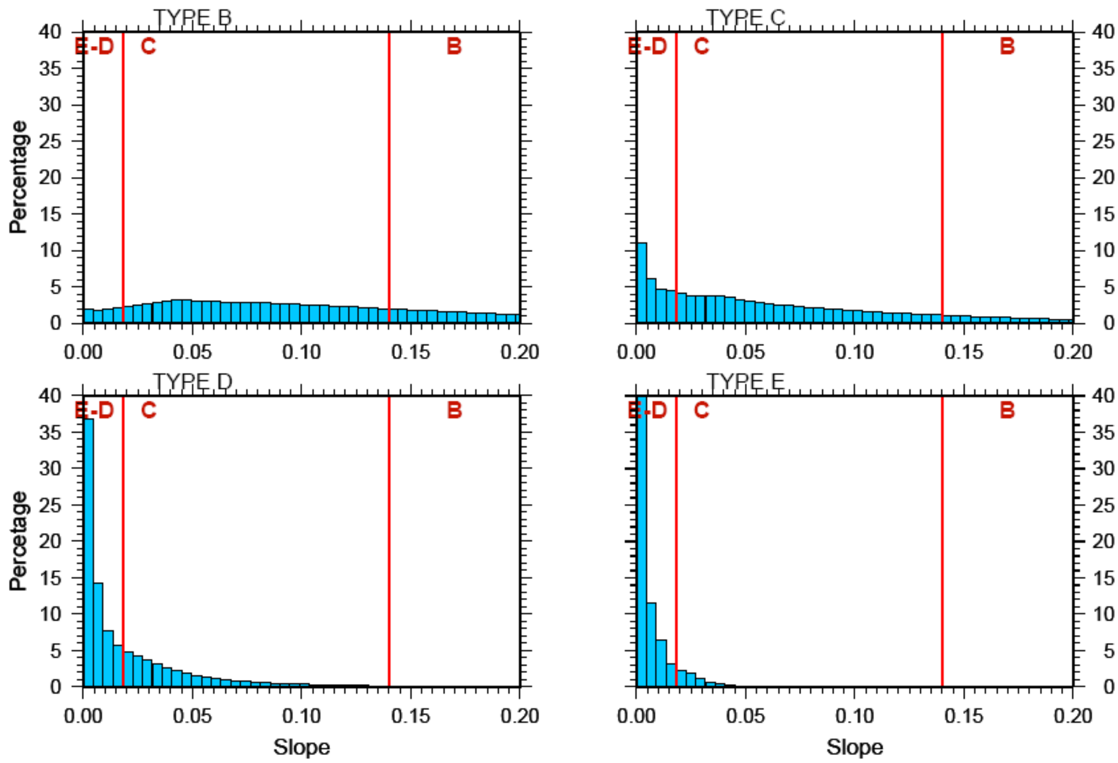

Figure 1. Histograms showing the percentage distribution slopes for each soil type inferred from geology in California.

For type B sites in the geology based map, about 57% of the cells has a Vs30 in the range of BC to B or harder based on slope data. The remaining 43% of the cells has an estimated Vs30 that mostly fall in the range of C to CD. Only 5% of the cells have a calculated Vs30 less than 360 m/s (type D or softer).

We did similar analyses in San Francisco and Los Angeles regions where larger scale geological maps (1:100,000) are available with more detailed geological information and finer spatial resolution (Table 2). Interpretation of geological data and mapping between geological units and NEHRP soil class followed the same procedure as that described in Wills et al. (2000). The soil class maps interpreted from geological data are rasterized to a grid of cells of about 100 meters in size. The slope is calculated using the same 9 arc-second topographic data. Table 2 shows that cells with type D soil in the geology based map mostly have a low Vs30 estimated from slope data with 78% corresponding to type D and 17% to type CD in San Francisco; and 67% of type D and 16% of type CD in Los Angeles. For type C cells in the geology based soil maps, 69% and 62% has Vs30 in the range of BC to CD in San Francisco and Los Angeles, respectively. For type B soil cells in the geology based soil maps, 59% and 63% has Vs30 in the range of BC to B in San Francisco and Los Angeles, respectively. Only about 1% of areas with B soil type in the geology based soil maps has Vs30 less than 360 m/s (type D).

Table 2. Percentage distribution of slope based soil types for each soil type from geology in San Francisco and Los Angeles. The sum in each column equals 100%.

Slope Based type	Soil Type from geology (San Francisco)			Soil Type from geology (Los Angeles)		
	B	C	D	B	C	D
B	35	28	0	38	14	6
BC	24	22	1	27	13	4
C	25	26	4	25	23	7
CD	15	21	17	10	26	16
D	1	4	78	1	24	67

Correlation Between Measured Vs30 and Vs30 Inferred from Geology and Topographic Slope

Both Wills et al (2000) and Allen and Wald (2009) have discussed how well did the seismic site condition maps inferred from geology or topographic slope compared with the measured Vs30. Here we do a similar analysis and tabulate the distribution of measured Vs30 for each soil type inferred from geology or topographic slope. Table 3 shows the percentage distribution of soil types estimated based on the measured Vs30 for each soil type inferred from geology. The Vs30 range for each soil class is shown in the heading of the table. The same range is used to convert the measured Vs30 to a soil type (the column heading). The measured Vs30 data are obtained from the NGA strong motion site classification database (Brian et al. 2008). 734 strong motion sites with Vs30 data from fall within the region and all are used in the analysis. Table 3 shows that 89% of the sites with measured Vs30 < 360 m/s fall in the areas of class D type on the geology based soil map, with another 7% fall in areas of class CD. A majority of measured Vs30 in areas of class C and CD have a shear wave velocity in the range 360-490 m/s, which corresponding to the Vs30 range of NEHRP CD or the lower half of class C soil. In class B areas, about 74% of the sites have measured Vs30 > 620 m/s, equivalent to class BC to B and harder. Overall the correlation between soil classes inferred from geology and measured shear wave velocity is very good. This good correlation is not surprising as a similar Vs30 data set was used by Wills et al. (2009) to grouping the geologic units and assigning soil types.

Table 4 shows the comparison of soil types inferred from the topographic slope with measured Vs30 data. For type D sites, the measured Vs30 are mostly low with 72% below 360 m/s (type D) and another 19% in the range of 360-490 m/s (CD type). In the type B areas, less than 30% of the measured Vs30 fall within the corresponding range (BC or B). The correlation between measured Vs30 and the Vs30 inferred from slope in the type C areas is better with about 75% of the measured Vs30 fall in the full Vs30 range for class C (from 360 m/s – 760 m/s). Overall the correlation between soil classes inferred from geology and the measured Vs30 is better than the correlation between the slope based soil classes and measured Vs30, especially in areas of firm soil to rock sites (classes C and B).

Table 3. Percentage distribution of soil types based on measured Vs30 for each soil type inferred from geology.

Geology based Soil types	Soil types and measured Vs30					
	B	BC	C	CD	D	
	Vs>760	620-760	490-620	360-490	<=360	total
B	19%	55%	7%	7%	12%	100%
C	2%	16%	7%	61%	14%	100%
CD	1%	3%	4%	68%	24%	100%
D	1%	1%	1%	7%	89%	100%

Table 4. Percentage distribution of soil types based on measured Vs30 for each soil type inferred from topographic slope.

Soil types based on Slope	Soil types and measured Vs30					
	B	BC	C	CD	D	
	Vs>760	620-760	490-620	360-490	<=360	total
B	16%	12%	39%	29%	4%	100%
C	4%	25%	25%	25%	21%	100%
CD	2%	4%	21%	34%	40%	100%
D	1%	1%	7%	19%	72%	100%

We also made the comparison between the measured Vs30 and Vs30 inferred from wither geology of topographic slope in terms of shear wave velocity (Figures 2 and 3). In the figures, the Vs30 from topographic slope is directly calculated from the slope based on the relationship by Allen and Wald (2009), whereas the median shear wave velocity value for each NEHRP soil type is used as the shear wave velocity in the calculation for the geology based soil types. As a reference, a difference by a factor of 2 between the measured and inferred Vs equivalent to a value of ±0.3 in the figure. Figure 2 shows that the difference between the measured Vs30 and the Vs30 inferred from geology is in general by less than a factor of 2, mostly less than a factor of 1.25 (0.1). The standard deviation of the log ratio of the difference is 0.11. The median value of the difference is slightly skewed to left off zero. This is primarily due to fact that the measured Vs30 in areas classified as type C and CD in the geology based soil map fall in the lower range of Vs30 assumed for the NEHRP type C soil (Table 3) as pointed out in above.

The statistics on the comparison between measured Vs30 and Vs30 inferred from slope is the same as those provided in Allen and Wald (2009) (see Figure 3). The difference between the measured Vs30 and Vs30 inferred from topographic slope is larger, with a standard deviation of 0.14 compared to the standard deviation of 0.11 from geological data.

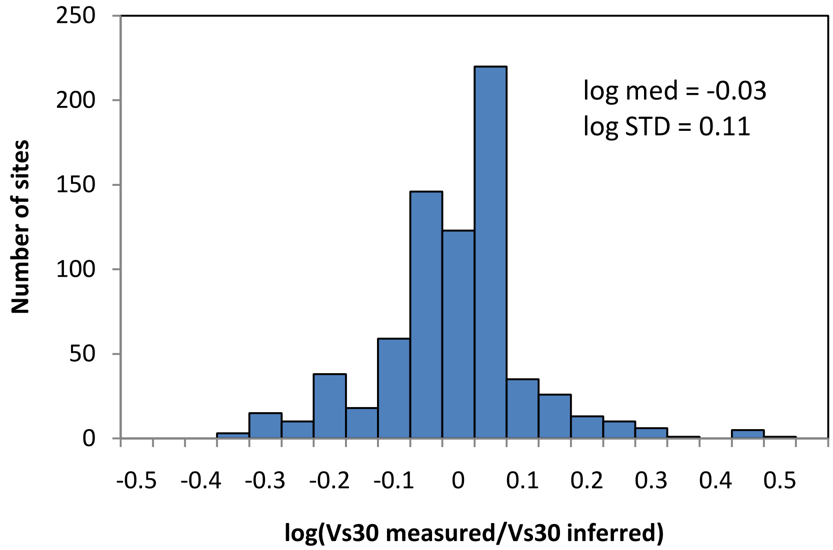

Figure 2. Histogram showing the differences of measured Vs30 and the Vs30 inferred from geology. The median Vs30 value is used for each soil class in the calculation.

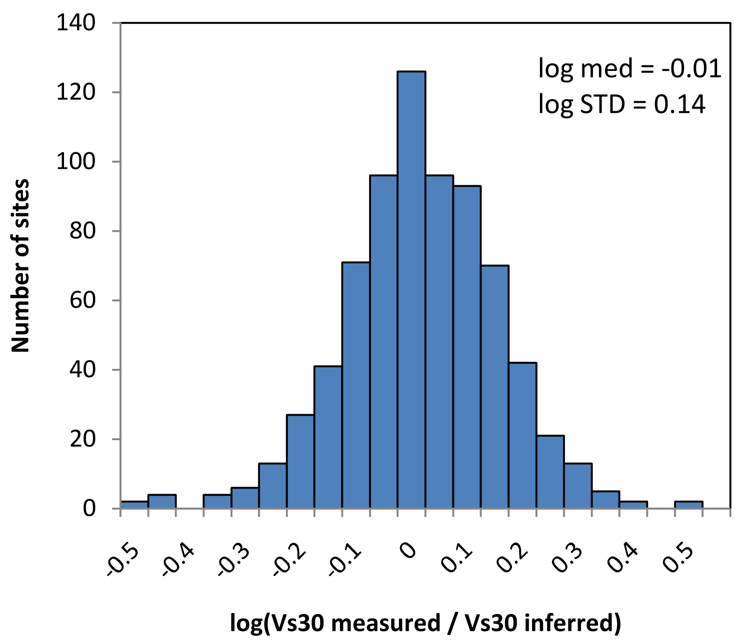

Figure 3. Histogram showing the differences of measured Vs30 and the Vs30 inferred from topographic slope.

Discussion and Conclusions

The good correlation between the D (and E) type of soils determined from geology and the D type inferred from topographic slope indicates that topographic slope can be used quite successfully to identify soft soil sites, as it was claimed by Wald and Allen (2007) and Allen and

Wald (2009). However for type C or B soil sites on the geology based soil maps, the correlation with the type inferred from topographic slope is inconclusive. Only about 60% of the type B or C sites inferred from geology have an estimated Vs30 that is within the range of NEHRP type B or C.

Comparisons between site classes inferred from geology or topographic slope and measured Vs30 indicate that soft soil sites inferred from both geology and topographic slope have low Vs30 values that fall in the soft soil catalog. Whereas the correlation between site classes B and C inferred from geology and those from measured Vs30 are also good, the correlation between slope based site classes in the B and C categories and those from measured Vs30 is not as good and is inconclusive.

Fumal and Tinsley (1985) found that the shear wave velocity of a soil depend to a large extent on the soil texture and relative grain size distribution of the soil. In an active depositional environment, the gain size of the sediment is largely controlled by the energy of the medium (e.g. flowing water) that transported the sediments. For sediments deposited from moving water (in rivers, streams, or lakes), the steeper the slope, the higher energy the moving water caries. As a result, on steeper slopes, the deposited sediments would have larger grain size (and also less sorted). Wald and Allen (2007) have argued that this may be the main reason why there is a good correlation between measured Vs 30 and Vs30 inferred from topographic slope, and that the Vs30 inferred from slope can be used as a good proxy for seismic site condition.

The same reason cannot be applied to sites that have firm or hard rock. Such sites are generally located in erosional environment. Wald and Allen (2007) argued that rock hardness and fracture spacing should correlate with topographic slope because hard rock and large fracture spacing both resist weathering, allowing rocks with higher Vs to hold a steeper slope. While this argument is generally true, there are other factors that affect topographic slope. For example, the duration of rock exposed to weathering and erosion, the uplifting rate of ground relative to sea level, state of deformation of the rock (folding and fracturing), and local weather etc. Tertiary and younger soft rocks such as sandstone or shale can develop steep slope in a short time period because of rapid erosion. The effect of duration and uplifting can easily be seen in modern river valleys where young Quaternary terraces along river banks maintain high slopes along the front of the terraces. Hence even though the properties of the sediment did not change from rear to front of a terrace, the slope changes, resulting in a much higher Vs30 estimation near the front edge of the terrace than the Vs30 estimated for the bulk of the terrace. The higher Vs30 estimated from slope along the edges of river terraces are clearly seen along the Mississippi river as shown by Allen and Wald (2009) when comparing the amplification factors using different resolution topographic data. Old erosion horizons exposed in mountain ridges can have very low slope because of the resistance of rock to weathering and/or slow erosion rate. Because of the complicated factors that control the slope of topography in erosional environment, it does not seem reliable to use slope to estimate Vs30 in such environment, as suggested by the statistic analysis result presented in this study.

Compared to the state wide comparison results, the result in Los Angeles and San Francisco shows that a significant percentage (16% to 17%) of type D cells in the geology based soil maps having a larger slope that would classify them as CD sites based on the slope data. The geological maps in San Francisco and Los Angeles have a larger scale (higher special resolution) and more details than the state wide geological map of California. When making geological maps at a smaller scale, geological units smaller than certain dimension, especially younger sediment units, are generally omitted. Thin layers of soils over basement rocks may also be ignored whenever the rock formation underneath can be reliable inferred. This is especially true along the edges of sedimentary basins or valleys. However such smaller sediment units are likely mapped on larger geological maps. Thus the main reason for why type D cells on larger geology bases soil maps have a larger percentage of cells on higher slope could be due to thin layer sediments mapped in the larger scale geological maps that are not on the smaller scale geological map. The more extensive distribution of younger sediments in larger scale geological maps has been noticed by Wills and Gutierrez (2007). Wills and Gutierrez (2007) also found that the sites that sit on quaternary sediments (D type) but near rock sites (mostly close to the edge of the sediment formation) and have steeper slope have relatively higher Vs30. They modified the mapping between geologic units and Vs30 by separating geological units based on their distance to rock and slope and found that the process can significantly improve the matching between geological site condition and measured Vs30. Therefore if the geological information is used together with the slope data, the site condition map can be improved.

In conclusion, we have shown based on the comparison of site classification maps developed from surface geology, topographic slope, and measured Vs30 that

1) Sites that are classified as NEHRP type D or E from surfacial geologic data are predominantly on slow topographic slopes and can be classified as type D or softer soil based on topographic data, indicating that both surfacial geological information and high resolution topographic data can be used to identify soft soil site conditions.
2) Topographic slope data cannot reliably distinguish type B sites from type C. Therefore should topographic slope be used as a proxy for site condition, a large uncertainty should be assigned to sites that are classified as type C or B when it used to calculate hazard maps.
3) Larger scale geological maps may contain areas with thin soil layers over firm or hard bedrock because of its higher spatial resolution and having more map details. Topographic slope data may help distinguish deep soft layers from thin soil layers at the edges of sedimentary basin or valley, thus help refine Vs30 estimations for young (late Tertiary to Quaternary) sediments.

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