Final Technical Report

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Title:

Shear-Velocity Measurements at CISN Stations Along the Southern San Andreas Fault

NEHRP Element(s):
ELEMENT I: National and regional earthquake hazards assessments.
ELEMENT III. Research on earthquake occurrence, physics, and effects.

Keywords: Site effects, Ground motions,Seismic zonation, Engineering seismology

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NON-TECHNICAL ABSTRACT

Measurement of shear velocity in the shallow subsurface is one part of the information needed to estimate earthquake hazards. Near-surface conditions affect the intensity of earthquake shaking. With our measurements we can estimate the expected ground motion and contribute towards the reduction of earthquake loss. As well, our measurements at newly installed California Integrated Seismic Network sites will serve to calibrate their earthquake recordings. This calibration will help improve seismologists' ability to predict earthquake ground shaking. We use the refraction microtremor method to make our measurements. In the rock of Southern California mountain peaks, our measurements continue to show softer ground conditions than those predicted previously.

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TECHNICAL ABSTRACT

Estimation of shallow shear velocities is a key element in the assessment of sites for potential earthquake ground shaking and damage. We assessed shallow conditions at 20 sites of strong- and weak-motion recording in Southern California near the southern San Andreas fault. We measured shear velocity as a function of depth using refraction-microtremor arrays placed at eleven new and upgraded stations funded by the USGS near the southern San Andreas fault trace, and also at nine other previously unmeasured ground-motion recording sites in the region. All sites yielded a shear-velocity profile to 30-100 m depth; we then computed the Vs30 average shear velocity from the surface to 30 m depth. We continued as well to study Southern California sites that have been included in the Next Generation Attenuation Equation (NGA) project. As part of the NGA project, the Pacific Earthquake Engineering Research Center used an updated correlation between geological units and shear velocity. This study showed poor correlation between geologic unit and Vs30 measurements. Many of the sites measured are on mountain promontories, where otherwise hard rocks have been heavily fractured and their velocities reduced. The measurements provide a better estimate of the site conditions at sites where strong ground motion has been recorded.

Prior measurements of Vs30 at seventy-nine sites throughout Southern California by two previous projects revealed varying comparisons against predicted Vs30 values. In the basin areas of the SCEC CVM version 4, the extrapolated Vs30 predictions match our new measurements well. Outside the basins, however, the SCEC CVM predicts much higher Vs30 values than we measured. When compared against Vs30 values we measured at 509 sites in Southern California and Nevada, the measured Vs30 values at 348 sites (68% of the sites) differed from the Wald & Allen topographic prediction by more than 20%. The Vs measurements we collected in this project provide further comparisons, and further information on how well site conditions can be predicted in the rocks of the Southern California mountains. In particular, we measured low velocities at the eleven ridgetop and mountaintop sites we characterized, with an average Vs30 at 494±157 m/s. All of these sites are in relatively old bedrock units, have very steep slopes, and are rapidly eroding. Yet they are producing Vs30 values mostly in the NEHRP C class, with all but GLA well below the NEHRP B-C boundary. Nevada graduate student Mayo Thompson completed his M.S. Geophysics thesis under this project in 2010.

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Introduction

This project obtained Vs30 and shear velocity profiles at twenty new, upgraded, and existing strong motion stations along the southern San Andreas fault in Southern California. It contributes toward the reduction of earthquake losses in the US by providing a more thorough characterization of the near-surface conditions of sites at which earthquake shaking has been measured. The results of this project will allow a more accurate assessment of the role that near-surface shear velocities play in amplifying ground motions. This project supported USGS NEHRP Elements I & III with "research that contributes to improvements in the national hazards maps and to assessing earthquake hazards and reducing losses in urban areas." It also supported "Priority Topics in Research on Earthquake Effects" by improving "site characterization for building code and other applications," and developing "quick and inexpensive methods to determine the shear-wave velocity profile at a site to a depth of about 200 m."

Measurement of shear-wave velocity (Vs) in the shallow subsurface is essential for the estimation of seismic hazard, the development of seismic-hazard maps, and for the calibration of recorded ground motion data. Previously, shallow shear velocities had been measured and released in Southern California by the USGS, the Rosrine project, and by the 214 site characterizations conducted along the San Gabriel River in 2003 under USGS-NEHRP sponsorship (Thelen et al., 2006). In 2006 and 2007, 78 site characterizations were conducted at ground-motion recording sites and other locations under USGS-NEHRP sponsorship (external grant award numbers 05HQGR0078 and 07HQGR0029) in an effort to assist development of the Next-Generation Attenuation (NGA) model. These assessments at sites of ground-motion recording, reported in Louie (2008) and by Dhar et al. (2008), allow more complete regressions of Northridge and later ground motions and spectra against other site parameters such as Vs100 and depths to interfaces. This study measured 20 additional locations, which, integrated with the

previous 78 measurements will contribute to microzonation studies of the Los Angeles and Coachella-Imperial basins, and to the national hazard mapping effort. We compared our shallow shear velocities measured by the refraction microtremor technique (Louie, 2001) against those predicted by the SCEC Community Velocity Model (CVM v. 4), against nearby Rosrine borehole data, and against the topographic predictions of Wald and Allen (2007).

The vertically averaged 30 m shear velocity (Vs30) is used to define NEHRP soil hazard classification for earthquake shaking as outlined by the NEHRP-UBC provisions (BSSC, 1997). Borehole sounding is a traditional method for obtaining Vs30. But, due to the high cost of borehole measurements, Louie (2001) developed the refraction microtremor technique (commercially available as SeisOpt®ReMi™) as a more rapid and cost-effective method of measuring Vs30 to meet the NEHRP-UBC code, and to derive site conditions. In this method, microtremor noise from sources such as traffic on streets and freeways excites Rayleigh waves, which are recorded over a half hour by a linear array of vertical refraction geophones. The noise records are transformed into slowness–frequency (*p-f*) space, and a dispersion curve picked along a minimum-velocity envelope. Modeling the dispersion curve produces a depth–velocity sounding, which can be vertically averaged to the single Vs30 value used by the NEHRP-UBC code.

Results from prior southern California projects 05HQGR0078 and 07HQGR0029

Shear-velocity profiles were measured at 78 CISN and strong-motion stations, and additional locations, in projects completed in January 2008. These projects were funded to measure the characteristics of ground-motion recording sites in Southern California, calibrating the sources of ground-motion data for prior and future earthquakes. Refraction microtremor data were processed and modeled independently by of Optim and by graduate students and faculty at UNR. The comparisons described below were conducted by Mayo Thompson and included in his Univ. of Nevada M.S. thesis in Geophysics (Thompson, 2010), and presented by him at three conferences (Thompson et al., 2009a;b;c)

A set of shear wave velocities were predicted at each measurement site using the Southern California Earthquake Center's Community Velocity Model (CVM), version 4. The CVM shear-wave velocities were obtained from the version 4 Fortran code at 0 and 30 meters depth. The Vs30 from the CVM was then calculated by the arithmetic slowness averaging formula above, assuming the 0-meter depth value represented 0-15 m depth and the 30-m depth value represented 15-30 m depth. This CVM Vs30 was then compared to our measured Vs30.

We obtained second set of Vs30 predictions from the earthquake.usgs.gov/vs30 web site (Wald and Allen, 2007). Wald and Allen predicted Vs30 from correlations of topographic slope derived from 900-m-interval DEMs, against a combination of Vs30 data sets, including Wills and Silva (1998), Scott et al. (2004), Scott et al. (2006), and Thelen et al. (2006). We chose Wald and Allen's prediction nearest to our measurement site for comparison.

Table 1 in Louie (2008) summarizes measurement array center locations, distance from the target CISN station, depths of resolution, and measured average shear velocities to 10-, 30-, 50-, and 100- meter depths, denoted by Vs10, Vs30, Vs50, and Vs100 respectively. Array centers were less than 70 meters from stations at over half of the sites. Depth of resolution was greater than 100 m for over half of the measurements. Among 2007 and prior measurement arrays, we observed the following high and low shear velocities (Table 1).

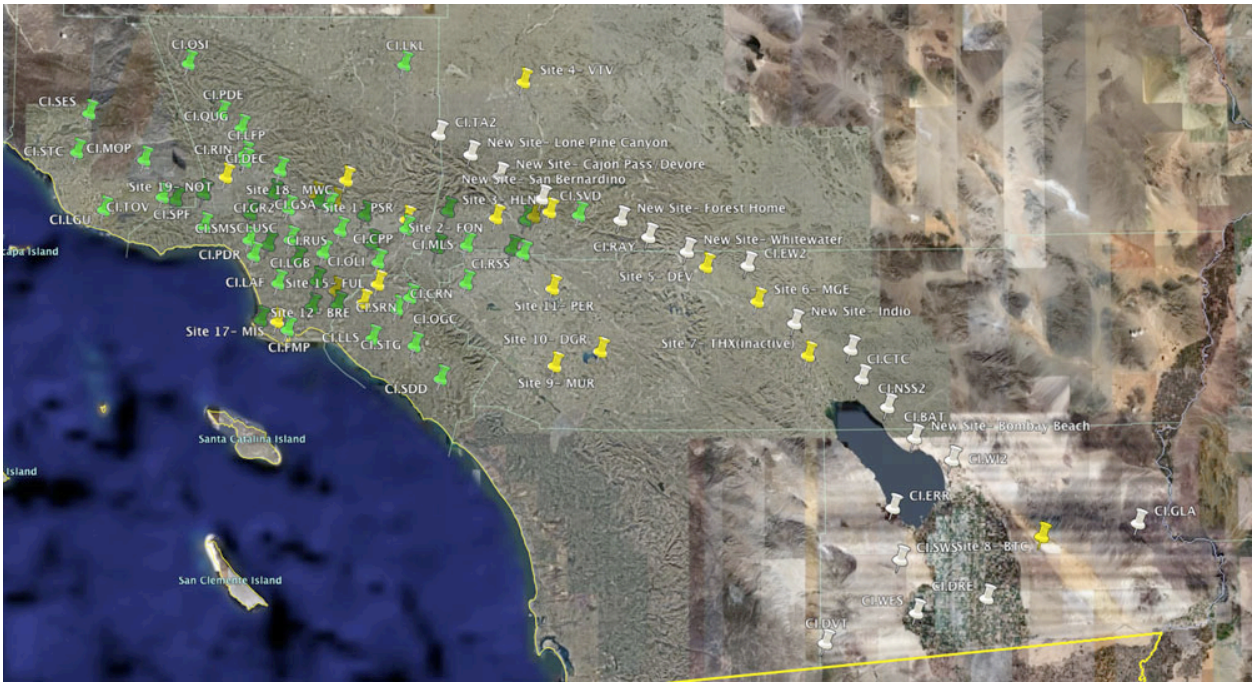

Figure 1. Google Earth map showing measurements made by prior UNR projects in 2006 (green), 2007 (yellow), and the 20 sites measured by this project in 2009-2010 (white). Map taken from Alan Yong and Sue Hough, USGS Pasadena office.

Locations	**High Vs10**	**Low Vs10**	**High Vs30**	**Low Vs30**	**High Vs50**	**Low Vs50**	**High Vs100**	**Low Vs100**
Prior, m/s	TOV **781**	LLS **148**	PFO1 **932**	LLS **218**	PFO1 **1133**	LLS **276**	PFO1 **1350**	LAF **339**
2007, m/s	CSMIP-1646 **596**	DLA **174**	CCSMIP-1646 **863**	DLA **233**	CSMIP-1646 **1044**	DLA **273**	CSMIP-1646 **1239**	BRE **385**

Table 1. High and low shear velocity depth-averages for measurements made in prior projects.

Table 3 in Louie (2008) summarizes the values of Z0.5, Z1.0 and Z1.5, which are the depths where the shear velocity first exceeds, or nearly exceeds, 0.5 km/s, 1.0 km/s and 1.5 km/s respectively. We also classified each site as rock or soil according to the Vs30 estimated in the SCEC CVM. Sites with Vs30 greater than 1200 m/s were considered as rock sites; sites with lower CVM Vs30s were considered soil sites (Table 4 of Louie, 2008).

The Vs30-value comparisons made by Thompson et al. (2009a;b;c) and by Thompson (2010) fell into three different categories. The Vs30 values from our measurements and predicted by the CVM differed by various amounts. The percent difference (CVM prediction minus measurement) was >600% for some sites with a maximum of 925% and a minimum of -72%. For the first group, differences ranged above 300%, with the SCEC CVM v4 far over-predicting Vs30. CVM velocities are from ~2100 to ~3400 m/s. For the second group, the differences ranged from 42% to 300%; the SCEC CVM has a surface velocity of 818.7 m/s and increases with depth to 30 m. For the third group, differences ranged <42% (including negative

differences, where the SCEC CVM under-predicts the measurement), and the CVM shows a Vs30 of 500 m/s or less.

The large difference in values between the SCEC CVM and our survey measurements could be explained by inspection of geologic maps of the area together with the rules inherent in the CVM. A first order look at the data revealed that the bulk of the measurements with large differences from the CVM lay on the edge of or outside the basin models defined by the CVM. The CVM predicts that anything that is outside modeled basins is hard rock (Magistrale et al., 2000; and the SCEC CVM v4 website), though there are no hard rock sites in California (Field, 2000). All the sites in the first, very over-predicted group of comparisons lie outside the CVM's basins, and our direct measurements reveal Vs30 values that are much lower than hard-rock shear velocities assumed by the CVM (Fig. 2). About 30 of the 73 sites measure to within ±20% of the CVM predictions; these tend to be within basins in deep soil. The set of sites showing moderate over-prediction by the CVM have been classed in the CVM as NEHRP C or B. The depth-averaged shear velocity to the depth of 30 m at both rock and soil sites were obtained by slowness averaging, which preserves the total vertical travel time of seismic waves along the profiles.

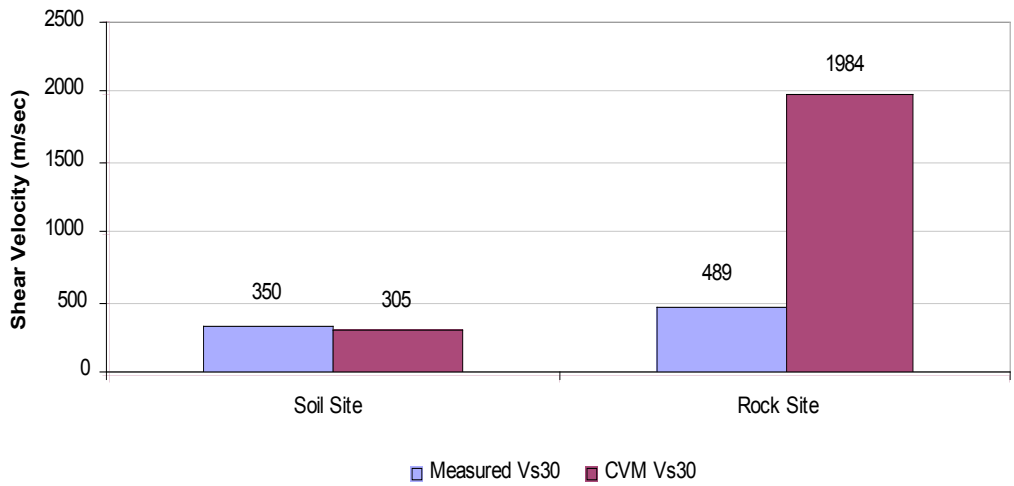

Figure 2. Comparison between slowness-averaged Vs30 values obtained from our prior measurements, and those predicted by the SCEC CVM, across all designated soil and all rock sites. Note over-prediction of Vs30 by the SCEC CVM at rock sites, as well as the minor under-prediction at soil sites. From Thompson (2010).

We also compared our Vs30 measurements with those of nearby Rosrine boreholes. For this we took two high-Vs30 Rosrine logs and two high Vs30 measurements (Fig. 3 in Louie, 2008). Similarly, we took two low-Vs30 Rosrine boreholes and two nearby low-velocity measurements (Fig. 4 in Louie, 2008).

Lastly, we compared 509 refraction microtremor measurements of Vs30 from California and Nevada against the nearest topographic predictions of Vs30 by Wald and Allen (2007), in Fig. 3. This data set includes the measurements published by Scott et al. (2004, 2006; green Xs and red squares in fig. 3), Thelen et al. (2006; dark red plusses), Pancha (2007; green diamonds), and reported by Louie (2008; orange circles and dark green bars). The additional data sets, not yet published, represent collaborations with DOE projects, and class and thesis work at UNR.

The data set covers a wide selection of sites: deep soil; thin soil; caliche-cemented soil; bouldery alluvium; weathered and fresh volcanic flows and tuffs; lake and estuary sediments; beach sands; granitic bedrock; and metasediments.

Of the 509 sites measured, Vs30 values were predicted within ±20% by Wald and Allen at only 161 sites, or 32% of cases. Figure 3 (right) shows that the 200 Southern California transect Vs30 measurements of Thelen et al. (2006) are consistently 20% or more above the topographic predictions. This mismatch appears despite the Wald and Allen (2007) regressions having included the Thelen et al. (2006) data.

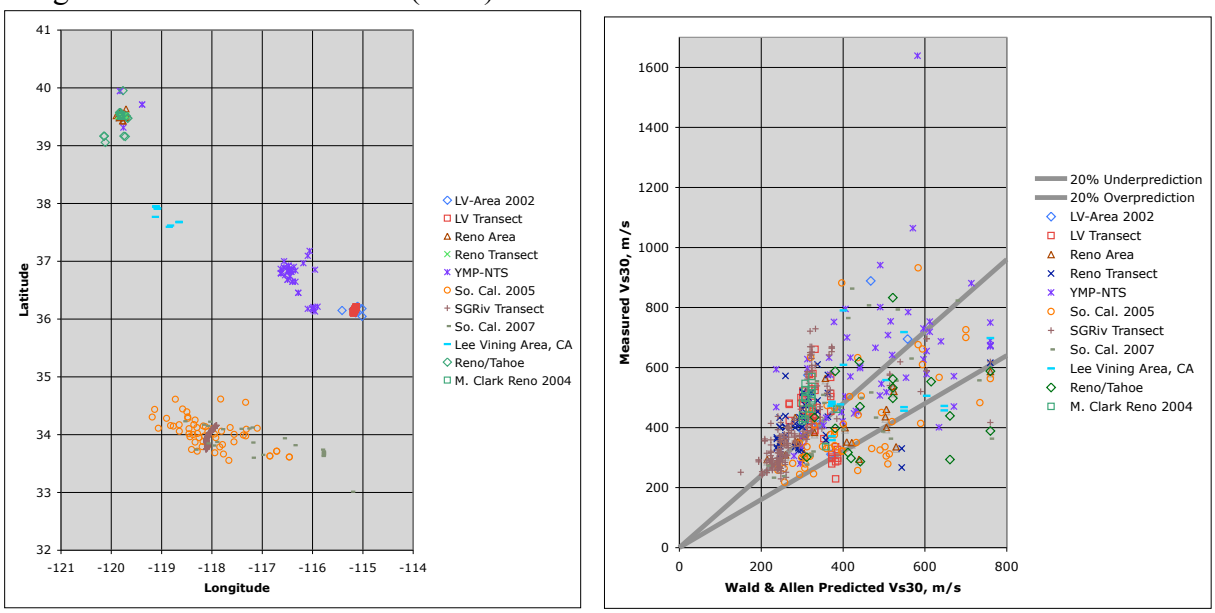

Figure 3. (left) Map showing relative locations of 509 Vs30 measurements in Southern California and Nevada. (right) Comparison of Wald and Allen (2007) predicted, and measured Vs30 values.

Methods and Results

This project was funded by the USGS to measure shear-wave velocity profiles at 20 sites of strong- and weak-motion recording in Southern California near the southern San Andreas fault. We measured shear velocity as a function of depth using refraction-microtremor arrays placed at eleven new and upgraded stations funded by the USGS near the southern San Andreas fault trace, and also at nine other previously unmeasured ground-motion recording sites in the region (Fig. 1). The data were collected in late 2009 and early 2010 using the refraction microtremor method (Louie, 2001). Data analysis was done using the commercial SeisOpt®ReMi™ software.

After analysis of the data and modeling of the depth–shear-velocity [$Vs(z)$] profile for each measured array, we computed the summary values of Vs30, for a depth range of 30 meters by arithmetic slowness averaging with the formula below:

$$VsZ = \frac{Z}{\sum_{1}^{N} \frac{z_i}{V_i}}$$

where Z is the total depth, z_i is the thickness of layer i with shear velocity V_i.

In detail, the work completed was as follows:

1. We measured a shallow shear-velocity profile at each of twenty sites of existing or planned CISN stations along the southern San Andreas fault and in Imperial Valley, using the techniques proven in our previous NEHRP-SC projects (e.g., Thelen et al., 2006; Stephenson et al., 2005; Louie, 2008; Dhar et al., 2008; Hauksson, 2010b). The measurements ere at stations in addition to the 78 CISN stations measured by Louie under 2006 and 2007 NEHRP-SC projects. Measurement tasks were supervised by John Louie.
    a) Stations to be measured were defined in consultation with Alan Yong of the USGS Pasadena office, so that sites of new CISN stations, and existing sites having poorly known geologic correlations with Vs were emphasized.
    b) Each station was measured by a 69- or 184-meter-long, 24-channel linear refraction microtremor array (Louie, 2001).
    c) The arrays were located on public access where possible, centered within 100 m of the stations, and recorded traffic microtremor for about a half hour.
    d) Optim SDS, the University of Nevada's commercial partner in refraction microtremor research and development, independently conducted field measurement, data analysis and modeling activities.

2. We modeled the microtremor data and velocity profiles. UNR and Optim conducted fully independent parallel analysis and modeling of all refraction microtremor data. John Louie conducted and supervised modeling activities:
    a) Each station's microtremor data was wavefield-transformed to slowness-frequency space.
    b) Rayleigh-wave dispersion was identified in slowness-frequency space, and a fundamental mode dispersion curve picked for each station.
    c) The dispersion curve was modeled (by Louie and students) or inverted (by Optim SDS), producing a shear-velocity-*vs.*-depth profile for each station. The modeling also produced assessments of depth of constraint, interface depths, and velocity-depth

tradeoffs. Inversions produced assessments of velocity uncertainties at different depths.

d) All field data and notes, dispersion data, and velocity profiles will be posted on the Vs archive web site http://crack.seismo.unr.edu/vs/archive in the standard formats, and supplied on a disc to Alan Yong of the USGS Pasadena office. The twenty pages of archive files are attached here as an Appendix.
e) Vs30 summary data were generated for each station from the modeled profiles, and posted on the web site as well.
f) Measurement results were communicated by Hauksson et al. (2010a), Louie et al. (2010), Thompson et al. (2009c), and Thompson (2010).

Comparison of Independent Interpretations

The data collected during the surveys were interpreted independently by two groups. The first interpretation was done by Optim SDS, while the second was done by Dr. Louie and students at the UNR Seismological Lab. The two interpretations provide a better understanding of the areas surveyed, along with model affirmation or invalidation. Using a 10% margin of error, we are able to determine which sites produce intetpretations that agree, and which do not.

- BOM provided Vs30 values from the two independent interpretations that were within the 10% margin of error, and because of this the Optim model should be used. The two models are slightly different in shape; they display similar structure, only at different depths. This difference can be attributed to a slight difference in trace picking and/or a difference in the interpreted depth of investigation.
- CJM, a mountaintop site, produced two almost identical models, with minimally variable velocities between the independent interpretations. The interface depth estimations are almost identical. The Vs30 values, however, differ by more than the 10% error window. The Optim model has more reasonable high velocities.
- CTC had two models that portrayed a similar shape, but because there was such a difference in dispersion picks on the *p-f* plots, the models cannot be comparable. The Vs30 data for both analyses are within 10% error. The UNR model is more of a spatial average, while the Optim model finds the two velocity increase that specifically underlies the CISN station. Since this is a station calibration project, we will use the more specific Optim model.
- DRE has differing models, but the Vs30 values are very close. In this case the Optim model is more descriptive of the low velocity setting in the Imperial Valley.
- DVT has independent Vs30 values that differ by an amount much exceeding the 10% threshold, with very dissimilar models. The discrepancy is due to differing initial dispersion picks made by each group. The Optim model is a better fit for the location and environment of this site, since Optim's picks recognized the high-frequency signal of the thin, low-velocity fill at this site.
- ERR, low in Imperial Valley, produced very similar models and Vs30 values between independent interpreters. The Optim model does a better job of considering the uncertainty of low-frequency dispersion picks, so we can accept that one.
- FHO produced differing models, but almost the same Vs30 values, from the independent analyses. While the dispersion picks from the *p-f* plots are similar, Optim's model is better fit to the most reliable picks.

- GLA is located on the hard rock ridge of Black Mountain, near radio facilities overlooking Glamis, Calif. These factors allow for a large jump in velocity at a shallow depth. The Optim model exhibits this large jump. Vs30 values for the two independent interpretations are slightly beyond the 10% margin of error. Optim and UNR interpreters followed different modes in the *p-f* plots. The UNR model is more of a spatial average, while the Optim model finds the sharp velocity increase that specifically underlies the CISN station. Since this is a station calibration project, we will use the more specific Optim model.
- IBP has independent Vs30 values that differ by an amount exceeding the 10% threshold, with somewhat dissimilar models. The discrepancy is due to differing initial dispersion traces and picks made by each group. Due to the variance in Vs30 values, we believe the Optim model is a better fit for the location and environment of this site.
- IPT has very different models and Vs30 values calculated by each group. The dispersion picks are very different. IPT is on a ridge above Waterman Can. in the San Bernardino Mts. Though the Optim interpretation appears to represent the higher-velocity rocks below the fractured ridgetop, the UNR interpretation may give a better volume average of the properties of the heavily fractured, rapidly eroding ridge. The UNR model pushes the interface to Vs=1000 m/s rock below 30 m depth, producing a much lower Vs30 than the Optim model. These observations lead us to conclude that the UNR model is the more representative and should be used for analysis. Seismograms recorded from IPT can be inspected for resonance at about 2.5 Hz, which would support the UNR model, or at about 4 Hz, which would support the Optim model.
- LPC shows Vs30 values that are within 10% from the intependent interpretations, and models that are comparable. The similarity in data and models allow for either interpretation to be used. The UNR model was interpreted deeper than may be warranted for the short ReMi arrays with 3-meter spacing, so we will use the Optim result..
- MSC has very similar Vs30 values, but the two models vary in form. The site is on a sharp, fractured ridge within a large canyon. Optim and UNR interpreters followed different modes in the *p-f* plots. The UNR model is more of a spatial average, while the Optim model finds the sharp velocity increase that specifically underlies the CISN station. Since this is a station calibration project, we will use the more specific Optim model.
- NSS2 has nearly identical models along with extremely similar Vs30 values (<0.3% difference). Either model, in this case, can be used, so we will pick the Optim model.
- SLB also has very similar Vs30 values between interpreters, but differing models. Optim picked higher frequencies than UNR, and UNR picked with more detail at the lower frequencies. Given the long array and relatively homogeneous location of the station, on a slight hill above the Salton Sea, we will select UNR's model as it is simpler, is a better volume average, and extends the depth coverage of the survey.
- SNO, atop Snow Peak in the San Bernardino Mts., yielded very different models as well as Vs30 values that exceed the 10% error threshold, from the interpendent interpreters. Optim and UNR interpreters followed different modes in the *p-f* plots. The UNR model is more of a spatial average, while the Optim model finds the sharp velocity increase that specifically underlies the CISN station. Since this is a station calibration project, we will use the more specific Optim model.

- SWS is on a southeastern foothill peak of Superstition Mtn. The Optim and UNR interpretations differ in Vs30 value, by more than 10%. The Optim model is very simple with only one layer, constituting a major jump in velocity, while the UNR model has a more complex layer interpretation. Optim and UNR interpreters followed different modes in the *p-f* plots. The UNR model is more of a spatial average, while the Optim model finds the sharp velocity increase that specifically underlies the CISN station. Given the relatively short ReMi array we will select the simpler Optim model.
- TA2, atop Table Mountain in the San Gabriel Mts., is a site that shows a very sharp increase in velocity between the artificial fill and weathered rock of the platform on the summit, and the much harder rock of the peak. The Vs30 values are quite different, as the Optim and UNR interpreters followed different modes in the *p-f* plots. The UNR model is more of a spatial average, while the Optim model finds the sharp velocity increase that specifically underlies the CISN station. Since this is a station calibration project, we will use the more specific Optim model.
- THM has Vs30 values differing by more than 10% from the independent interpretations, with models that differ in the depth of the deepest interface interpreted. We pick the Optim model, which is more internally consistent.
- WES, Westmoreland in the Imperial Valley has similar Vs30 values and very similar models. The dispersion picks from both UNR and Optim both utilize the majority of the frequency spectrum and are very close to each other. Either model could be used so we will use Optim's model.
- WWC, West Wide Canyon on the southern edge of the Pinto Mountains has Vs30 values from the separate analyses that are outside the 10% threshold, but both interpretations provide similar models. The site lies on a mid-level weathered ridge; because of this we believe the Optim model is more accurate since it exhibits a lower overall velocity and Vs30 value.

Final Results

Station	Midpoint of ReMi Array Lat	Long	Dist. from Station, m	Depth of Model, m	Vs30, m/s
BOM	33.36431	-115.72900	70	100	197
CJM	34.27131	-117.42406	<27	60	472
CTC	33.65483	-115.98978	45	50	293
DRE	32.80517	-115.44675	15	60	189
DVT	32.65905	-116.10024	36	30	705
ERR	33.11592	-115.82251	93	60	241
FHO	34.09317	-116.93581	42	40	434
GLA	33.05141	-114.82734	28	50	836
IBP	32.66105	-116.09315	28	80	547
IPT	34.19710	-117.28520	1	50	297

Station	Midpoint of ReMi Array Lat	Long	Dist. from Station, m	Depth of Model, m	Vs30, m/s
LPC	34.31460	-117.54604	40	40	512
MSC	34.03887	-116.64815	43	40	341
NSS2	33.55552	-115.94594	8	50	313
SLB	33.48597	-115.86649	86	90	372
SNO	34.03522	-116.80783	9	50	404
SWS	32.94509	-115.80019	16	30	438
TA2	34.38226	-117.67807	29	40	429
THM	33.65078	-116.07688	45	60	367
WES	32.75905	-115.73149	13	100	241
WWC	33.94097	-116.40854	38	80	531

Table 1: Shallow shear velocity measured with the ReMi technique by the University of Nevada and Optim SDS, at the locations of twenty CISN stations in Southern California, most along the southern San Andreas fault. The given geographic coordinates are in the WGS84 datum, and all are within 100 meters of the target CISN seismometer.

Discussion

One issue is how Vs depends on topographic elevation and slope, soil composition, geologic age, or provenance. We measured low velocities at the eleven ridgetop and mountaintop sites we characterized (CJM, DVT, FHO, GLA, IBP, IPT, MSC, SNO, SWS, TA2, WWC), with an average Vs30 at these sites of 494±157 m/s. The maximum was 836 m/s at GLA and the minimum was 297 m/s at IPT. All of these sites are in relatively old bedrock units, have very steep slopes, and are rapidly eroding. Yet they are producing Vs30 values mostly in the NEHRP C class, with all but GLA well below the NEHRP B-C boundary. In Southern California, as noted by Thompson et al. (2009a;b;c) and Thompson (2010), only deep soil sites show Vs30 values that are reliably predictable from any of these other observables. Rock sites are unpredictably variable, and if anything get softer as topographic slope increases. That is the inverse of the relationship proposed by Wald and Allen (2007).

One implication of this observation, also noted by Thompson et al. (2009a;b;c) and Thompson (2010), is that there can be no effective means of interpolating Vs30 between rock-site measurements. Louie et al. (2011) showed a data set of over 10,000 ReMi measurements in Las Vegas, Nevada, that includes hundreds of measurements at rock sites and in mountainous areas. This very comprehensive data set shows little predictability from any of the factors of topographic elevation and slope, soil composition, geologic age, or provenance.

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Appendix

Twenty Geotechnical Archive Files
One Per CISN Station

Site name: CISN-SC Station BOM, Bombay Beach, Salton Sea, Calif.
Lat/long: 33.36431/-115.72900 WGS84
Seismic Station Location Lat/Long: 33.36465/-115.72963 WGS84
Array Center Distance to Station: 70 m
Array Azimuth, degrees: N50E
Geophone Spacing: 8 m
Average velocity to 30 m, m/s: 197
Date: 11/09/09 (dd/mm/yy)
Performed by: Optim SDS
Type of measurements: ReMi
Depth of measurements: 100 m
Function stepped (y or n): yes
Posted by: J. Louie (24/12/11)

Depth(m)	Vs(m/s)
0.0	122
1.1	122
1.1	139
2.9	139
2.9	143
4.8	143
4.8	185
12.2	185
12.2	220
27.6	220
27.6	308
79.8	308
79.8	680
100	680

Site name: CISN-SC Station CJM, Southern San Andreas fault, Cajon Mountain, San Bernardino Mts., Calif.
Lat/long: 34.27131/-117.42406 WGS84
Seismic Station Location Lat/Long: 34.271308/-117.424059 WGS84
Array Center Distance to Station: <27 m
Array Azimuth, degrees: N40E
Geophone Spacing: 3 m
Average velocity to 30 m, m/s: 472
Date: 22/10/09 (dd/mm/yy)
Performed by: Optim SDS
Type of measurements: ReMi
Depth of measurements: 60 m
Function stepped (y or n): yes
Posted by: J. Louie (24/12/11)

Depth(m)	Vs(m/s)
0.0	203
2.1	203
2.1	330
5.9	330
5.9	467
18.9	467
18.9	779
44.3	779
44.3	1798
60	1798

Site name: CISN-SC Station CTC, Cactus City, Mecca Hills, Calif.
Lat/long: 33.65483/-115.98978 WGS84
Seismic Station Location Lat/Long: 33.65516/-115.99006 WGS84
Array Center Distance to Station: 45 m
Array Azimuth, degrees: N62W
Geophone Spacing: 3 m
Average velocity to 30 m, m/s: 293
Date: 11/09/09 (dd/mm/yy)
Performed by: Optim SDS
Type of measurements: ReMi
Depth of measurements: 50 m
Function stepped (y or n): yes
Posted by: J. Louie (24/12/11)

Depth(m)	Vs(m/s)
0.0	121
3.6	121
3.6	161
11.9	161
11.9	805
32.9	805
32.9	1469
50	1469

Site name: CISN-SC Station DRE, Meloland, Imperial Val., Calif.
Lat/long: 32.80517/-115.44675 WGS84
Seismic Station Location Lat/Long: 32.8053/-115.44679 WGS84
Array Center Distance to Station: 15 m
Array Azimuth, degrees: N0E
Geophone Spacing: 3 m
Average velocity to 30 m, m/s: 189
Date: 02/11/09 (dd/mm/yy)
Performed by: Optim SDS
Type of measurements: ReMi
Depth of measurements: 60 m
Function stepped (y or n): yes
Posted by: J. Louie (24/12/11)

Depth(m)	Vs(m/s)
0.0	101
2.4	101
2.4	185
21.5	185
21.5	261
53.6	261
53.6	509
60	509

Site name: CISN-SC Station DVT, Desert View Tower, Boulder Park, Jacumba Mts., Calif.
Lat/long: 32.65905/-116.10024 WGS84
Seismic Station Location Lat/Long: 32.65915/-116.1006 WGS84
Array Center Distance to Station: 36 m
Array Azimuth, degrees: N60W
Geophone Spacing: 3 m
Average velocity to 30 m, m/s: 705
Date: 23/10/09 (dd/mm/yy)
Performed by: Optim SDS
Type of measurements: ReMi
Depth of measurements: 30 m
Function stepped (y or n): yes
Posted by: J. Louie (24/12/11)

Depth(m)	Vs(m/s)
0.0	168
1.2	168
1.2	276
2.3	276
2.3	394
4.7	394
4.7	680
17.1	680
17.1	1708
30	1708

Site name: CISN-SC Station ERR, Elmore Ranch Road, Kane Spring, Imperial Val., Calif.
Lat/long: 33.11592/-115.82251 WGS84
Seismic Station Location Lat/Long: 33.11675/-115.82267 WGS84
Array Center Distance to Station: 93 m
Array Azimuth, degrees: N10W
Geophone Spacing: 8 m
Average velocity to 30 m, m/s: 241
Date: 23/10/09 (dd/mm/yy)
Performed by: Optim SDS
Type of measurements: ReMi
Depth of measurements: 60 m
Function stepped (y or n): yes
Posted by: J. Louie (24/12/11)

Depth(m)	Vs(m/s)
0.0	153
2.1	153
2.1	182
6.7	182
6.7	222
12.3	222
12.3	246
21.8	246
21.8	369
47.0	369
47.0	874
60	874

Site name: CISN-SC Station FHO, Southern San Andreas fault, Forest Home, Mill Creek, San Bernardino Mts., Calif.
Lat/long: 34.09317488/-116.9358106 WGS84
Seismic Station Location Lat/Long: 34.09355/-116.93588 WGS84
Array Center Distance to Station: 42 m
Array Azimuth, degrees: N20E
Geophone Spacing: 3 m
Average velocity to 30 m, m/s: 434
Date: 10/09/09 (dd/mm/yy)
Performed by: Optim SDS
Type of measurements: ReMi
Depth of measurements: 40 m
Function stepped (y or n): yes
Posted by: J. Louie (24/12/11)

Depth(m)	Vs(m/s)
0.0	165
4.7	165
4.7	351
12.0	351
12.0	1004
24.7	1004
24.7	1475
40	1475

Site name: CISN-SC Station GLA, Black Mountain, Glamis, Calif.
Lat/long: 33.05141/-114.82734 WGS84
Seismic Station Location Lat/Long: 33.05149/-114.82706 WGS84
Array Center Distance to Station: 28 m
Array Azimuth, degrees: N50W
Geophone Spacing: 3 m
Average velocity to 30 m, m/s: 836
Date: 02/11/09 (dd/mm/yy)
Performed by: Optim SDS
Type of measurements: ReMi
Depth of measurements: 50 m
Function stepped (y or n): yes
Posted by: J. Louie (24/12/11)

Depth(m)	Vs(m/s)
0.0	301
7.8	301
7.8	2134
33.0	2134
33.0	2751
50	2751

Site name: CISN-SC Station IBP, Boulder Park, Jacumba Mts., Calif.
Lat/long: 32.66105/-116.093581 WGS84
Seismic Station Location Lat/Long: 32.66112/-116.09286 WGS84
Array Center Distance to Station: 28 m
Array Azimuth, degrees: N76E
Geophone Spacing: 3 m
Average velocity to 30 m, m/s: 547
Date: 16/04/10 (dd/mm/yy)
Performed by: Optim SDS
Type of measurements: ReMi
Depth of measurements: 80 m
Function stepped (y or n): yes
Posted by: J. Louie (24/12/11)

Depth(m)	Vs(m/s)
0.0	276
1.7	276
1.7	384
6.0	384
6.0	596
22.7	596
22.7	751
38.0	751
38.0	1095
69.8	1095
69.8	2224
80	2224

Site name: CISN-SC Station IPT, Southern San Andreas fault, Waterman Canyon, San Bernardino Mts., Calif.
Lat/long: 34.19710/-117.28520 WGS84
Seismic Station Location Lat/Long: 34.197109/-117.285194 WGS84
Array Center Distance to Station: 1 m
Array Azimuth, degrees: N60W
Geophone Spacing: 3 m
Average velocity to 30 m, m/s: 297
Date: 22/10/09 (dd/mm/yy)
Performed by: Optim SDS
Type of measurements: ReMi
Depth of measurements: 50 m
Function stepped (y or n): yes
Posted by: J. Louie (24/12/11)

Depth(m)	Vs(m/s)
0.0	208
2.4	208
2.4	262
11.1	262
11.1	336
30.9	336
30.9	712
35.8	712
35.8	1255
50	1255

Site name: CISN-SC Station LPC, Southern San Andreas fault, Lone Pine Canyon, San Gabriel Mts., Calif.
Lat/long: 34.31460358/-117.5460419 WGS84
Seismic Station Location Lat/Long: 34.31478/-117.54642 WGS84
Array Center Distance to Station: 40 m
Array Azimuth, degrees: N60W
Geophone Spacing: 3 m
Average velocity to 30 m, m/s: 512
Date: 10/09/09 (dd/mm/yy)
Performed by: Optim SDS
Type of measurements: ReMi
Depth of measurements: 40 m
Function stepped (y or n): yes
Posted by: J. Louie (24/12/11)

Depth(m)	Vs(m/s)
0.0	222
1.4	222
1.4	331
3.6	331
3.6	488
24.3	488
24.3	1455
40	1455

Site name: CISN-SC Station MSC, Southern San Andreas fault, Mission Creek, San Bernardino Mts., Calif.
Lat/long: 34.03887/-116.64815 WGS84
Seismic Station Location Lat/Long: 34.03852/-116.64795 WGS84
Array Center Distance to Station: 43 m
Array Azimuth, degrees: N25W
Geophone Spacing: 3 m
Average velocity to 30 m, m/s: 341
Date: 10/09/09 (dd/mm/yy)
Performed by: Optim SDS
Type of measurements: ReMi
Depth of measurements: 40 m
Function stepped (y or n): yes
Posted by: J. Louie (24/12/11)

Depth(m)	Vs(m/s)
0.0	137
3.1	137
3.1	174
10.8	174
10.8	702
22.9	702
22.9	1404
40	1404

Site name: CISN-SC Station NSS2, Southern San Andreas fault, Coachella Canal, Calif.
Lat/long: 33.55552/-115.94594 WGS84
Seismic Station Location Lat/Long: 33.55553/-115.94585 WGS84
Array Center Distance to Station: 8 m
Array Azimuth, degrees: N50W
Geophone Spacing: 3 m
Average velocity to 30 m, m/s: 313
Date: 11/09/09 (dd/mm/yy)
Performed by: Optim SDS
Type of measurements: ReMi
Depth of measurements: 50 m
Function stepped (y or n): yes
Posted by: J. Louie (24/12/11)

Depth(m)	Vs(m/s)
0.0	212
5.2	212
5.2	285
9.6	285
9.6	301
17.2	301
17.2	412
40.2	412
40.2	874
50	874

Site name: CISN-SC Station SLB, Southern San Andreas fault, Desert Air Sky Ranch, Salton Sea, Calif.
Lat/long: 33.48597/-115.86649 WGS84
Seismic Station Location Lat/Long: 33.48519/-115.86643 WGS84
Array Center Distance to Station: 86 m
Array Azimuth, degrees: N1E
Geophone Spacing: 8 m
Average velocity to 30 m, m/s: 372
Date: 11/09/09 (dd/mm/yy)
Performed by: Optim SDS
Type of measurements: ReMi
Depth of measurements: 90 m
Function stepped (y or n): yes
Posted by: J. Louie (24/12/11)

Depth(m)	Vs(m/s)
0.0	305
12.5	305
12.5	441
32.0	441
32.0	735
45.5	735
45.5	1315
73.0	1315
73.0	1494
90	1494

Site name: CISN-SC Station SNO, Southern San Andreas fault, Snow Peak, San Bernardino Mts., Calif.
Lat/long: 34.03522/-116.80783 WGS84
Seismic Station Location Lat/Long: 34.03515/-116.80778 WGS84
Array Center Distance to Station: 9 m
Array Azimuth, degrees: N5W
Geophone Spacing: 3 m
Average velocity to 30 m, m/s: 404
Date: 22/10/09 (dd/mm/yy)
Performed by: Optim SDS
Type of measurements: ReMi
Depth of measurements: 50 m
Function stepped (y or n): yes
Posted by: J. Louie (24/12/11)

Depth(m)	Vs(m/s)
0.0	127
2.5	127
2.5	231
12.3	231
12.3	1360
36.4	1360
36.4	1744
50	1744

Site name: CISN-SC Station SWS, Superstition Mountain Weather Sta., Imperial Val., Calif.
Lat/long: 32.94509/-115.80019 WGS84
Seismic Station Location Lat/Long: 32.945/-115.800 WGS84
Array Center Distance to Station: 16 m
Array Azimuth, degrees: N78W
Geophone Spacing: 3 m
Average velocity to 30 m, m/s: 438
Date: 23/10/09 (dd/mm/yy)
Performed by: Optim SDS
Type of measurements: ReMi
Depth of measurements: 30 m
Function stepped (y or n): yes
Posted by: J. Louie (24/12/11)

Depth(m)	Vs(m/s)
0.0	171
6.2	171
6.2	171
9.2	171
9.2	1376
30	1376

Site name: CISN-SC Station TA2, Southern San Andreas fault, Table Mountain, San Gabriel Mts., Calif.
Lat/long: 34.38226/-117.67807 WGS84
Seismic Station Location Lat/Long: 34.38203/-117.67822 WGS84
Array Center Distance to Station: 29 m
Array Azimuth, degrees: N8W
Geophone Spacing: 3 m
Average velocity to 30 m, m/s: 429
Date: 22/10/09 (dd/mm/yy)
Performed by: Optim SDS
Type of measurements: ReMi
Depth of measurements: 40 m
Function stepped (y or n): yes
Posted by: J. Louie (24/12/11)

Depth(m)	Vs(m/s)
0.0	110
2.6	110
2.6	132
4.9	132
4.9	149
6.9	149
6.9	1179
14.7	1179
14.7	1552
26.8	1552
26.8	1705
40.0	1705

Site name: CISN-SC Station THM, Southern San Andreas fault, Thermal, Coachella Val., Calif.
Lat/long: 33.65078/-116.07688 WGS84
Seismic Station Location Lat/Long: 33.65066/-116.07734 WGS84
Array Center Distance to Station: 45 m
Array Azimuth, degrees: N73E
Geophone Spacing: 3 m
Average velocity to 30 m, m/s: 367
Date: 11/09/09 (dd/mm/yy)
Performed by: Optim SDS
Type of measurements: ReMi
Depth of measurements: 60 m
Function stepped (y or n): yes
Posted by: J. Louie (24/12/11)

Depth(m)	Vs(m/s)
0.0	200
1.1	200
1.1	344
6.1	344
6.1	394
35.0	394
35.0	968
60	968

Site name: CISN-SC Station WES, Westmoreland, Imperial Val., Calif.
Lat/long: 32.75905/-115.73149 WGS84
Seismic Station Location Lat/Long: 32.759/-115.73161 WGS84
Array Center Distance to Station: 13 m
Array Azimuth, degrees: N0E
Geophone Spacing: 8 m
Average velocity to 30 m, m/s: 241
Date: 02/11/09 (dd/mm/yy)
Performed by: Optim SDS
Type of measurements: ReMi
Depth of measurements: 100 m
Function stepped (y or n): yes
Posted by: J. Louie (24/12/11)

Depth(m)	Vs(m/s)
0.0	106
3.6	106
3.6	228
11.2	228
11.2	324
57.5	324
57.5	664
100	664

Site name: CISN-SC Station WWC, Southern San Andreas fault, West Wide Canyon, Pinto Mts., Calif.
Lat/long: 33.94097/-116.40854 WGS84
Seismic Station Location Lat/Long: 33.94068/-116.40876 WGS84
Array Center Distance to Station: 38 m
Array Azimuth, degrees: N30E
Geophone Spacing: 3 m
Average velocity to 30 m, m/s: 531
Date: 10/09/09 (dd/mm/yy)
Performed by: Optim SDS
Type of measurements: ReMi
Depth of measurements: 80 m
Function stepped (y or n): yes
Posted by: J. Louie (24/12/11)

Depth(m)	Vs(m/s)
0.0	175
1.5	175
1.5	296
4.0	296
4.0	535
11.8	535
11.8	636
22.3	636
22.3	865
48.8	865
48.8	1461
80.0	1461