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A Shallow Shear-Wave Velocity Transect across the Reno, Nevada, Area Basin

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Abstract In October and November 2001, we performed an urban shear-wave velocity transect across 16 km of the Reno, Nevada, area basin. Using the refraction microtremor method of Louie (2001) we determined shear-wave velocity versus depth profiles at 55 locations. Shear-wave velocity averaged to 30 m depth (Vs30) is one predictor of earthquake ground-motion amplification in similar alluvium-filled basins, and it is the basis of site hazard classification under National Earthquake Hazards Reduction Program-Uniform Building Code (NEHRP-UBC) provisions. A geologic map-based NEHRP classification along nearly all of our transect line would be NEHRP-D, but our measurements of Vs30 revealed that 82% of the transect is classified NEHRP-C. Relatively stiff Tertiary sediments underlie the surface of the Reno basin, and weaker soils occur east of downtown Reno in the floodplain of the Truckee River. Although 53 of our locations were on the geologically youngest and most active fluvial units, these sites showed Vs30 values ranging from 286 m/sec (NEHRP-D) to 849 m/sec (NEHRP-B). Mapped geologic and soil units are not accurate predictors of Vs30 measurements in this urban area. A test model based on gravity results showed Quaternary-alluvium depth can be combined with transect Vs30 measurements to predict Vs30 across the Reno basin.

Introduction

For 9 days in October and November of 2001, we conducted a refraction microtremor experiment across 16 km of the basin surrounding the cities of Reno and Sparks, Nevada (Fig. 1). The purpose of the study was to determine the National Earthquake Hazards Reduction Program (NEHRP) site classifications along the transect by providing a large number of measurements of shear-wave velocity to 30 m depth (Vs30). Vs30 is the shear-wave velocity averaged to 30 meters depth and is one predictor of earthquake ground-motion amplification and potential hazard in similar alluvium-filled basins in California (Field *et al.*, 2000). Under NEHRP-Uniform Building Code (UBC, 1997) provisions (Building Seismic Safety Council [BSSC], 1998) sites are categorized for shaking hazard using Vs30. Because of the costs of the borehole and penetrometer measurement methods (e.g., American Society For Testing and Materials [ASTM] standards D4428 and D5778), site classification in the Reno area was previously based largely on geological maps with sparse downhole measurement support. Wills *et al*. (2000) prepared a site-conditions map for California on this basis. Although Cashman and Fontaine (2000) describe the Reno basin and its surroundings as being geologically similar to nearby California basins, the economics of site characterization had forced acceptance of what may be an overly conservative map-based classification in the Reno area. We set out to make a sufficient number of shear-wave velocity measurements in the basin to be able to assess the success of alternative NEHRP classification and mapping strategies.

Methods

Our shear-wave velocity characterizations of the Reno basin were based on the refraction microtremor technique (Louie, 2001), which provided an economical new approach to Vs30 estimation. Ambient seismic noise (vehicle traffic, etc.) excited Rayleigh waves in urban alluvium, eliminating the need for an explosive or hammer source. A noisy urban environment was thus advantageous to this method. We recorded the Rayleigh waves with a 300-m-long array of vertical geophones. Our array records were transformed into slowness-frequency space; dispersion was picked and then forward-modeled to produce a velocity-depth profile. Vs30 values were summarized from the profiles.

Our transect nearly coincided with an earlier study of Neogene basin depth by Abbott and Louie (2000). They produced a 2D depth profile of the Reno basin based on gravity modeling supported by borehole data. Their model depths for each of our transect points are shown in Figure 2.

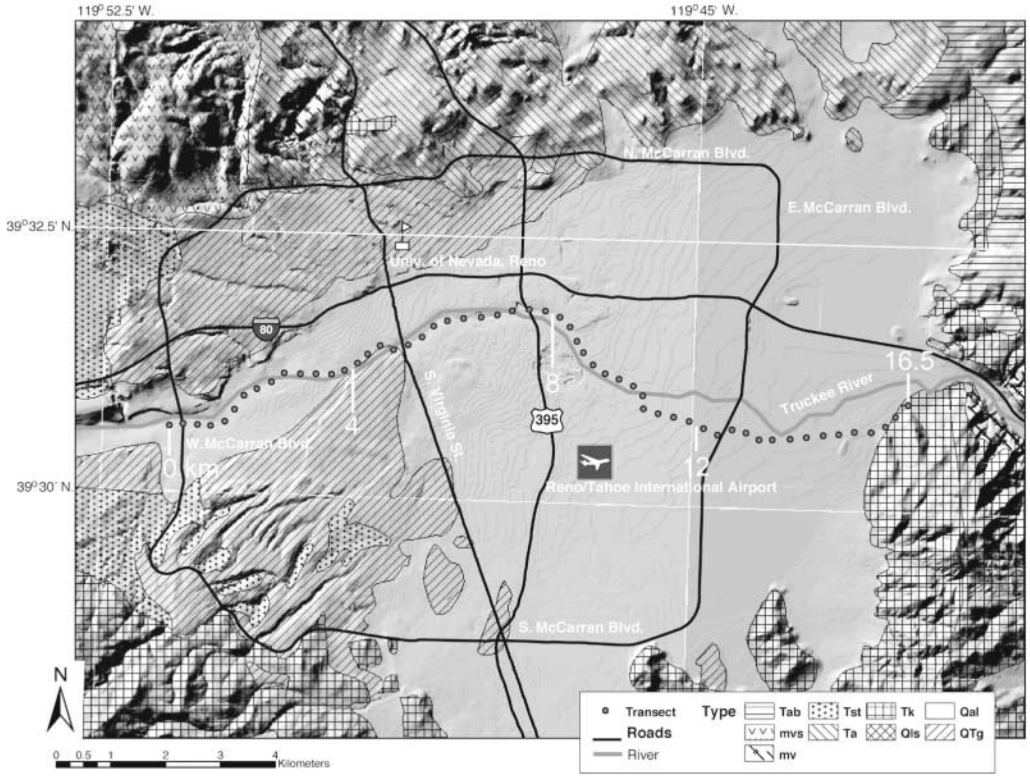

Figure 1. Map showing the location of our transect across the Reno–Sparks, Nevada, urban basin. Dots mark the locations of the end points of each 300-m-long segment of the microtremor-recording arrays. Large white numerals indicate distances along the transect from its west end. Regionally grouped geologic units from the NBMG Washoe County Digital Geologic Map (2000) are: **mv**, Peavine Sequence, metavolcanic rocks; **mvs**, Peavine Sequence, undifferentiated metavolcanics/metasediments; **Qal**, stream deposits; **Qls**, landslide deposits; **Qtg**, pre-Lake Lahontan deposits; **Ta**, Alta Formation; **Tab**, basalt, basaltic, and andesite; **Tk**, Kate Peak formation, flows, or flow breccia; **Tst**, Pliocene sedimentary rocks.

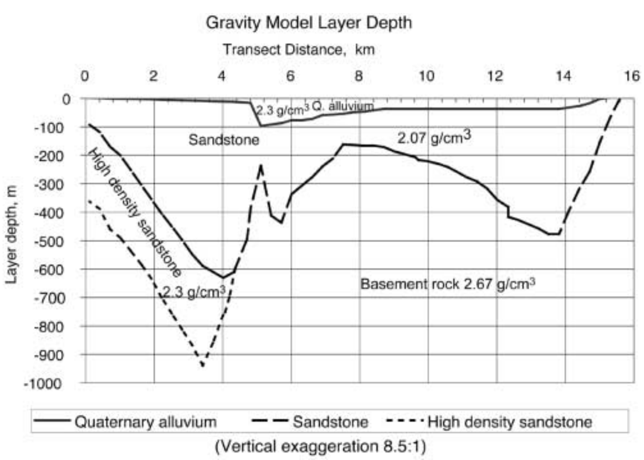

Figure 2. Depth-of-alluvium and depth-to-basement-rock profile for points along our transect (Fig. 1) from the gravity model of Abbott and Louie (2000). The densities of each rock unit used in modeling are shown. Refer to Figure 1 for geographical reference of transect distances.

For our arrays we used 45 Ref Tek RT-125 "Texan" seismographs mated to 4.5-Hz vertical geophones (courtesy of the PASSCAL Instrument Center at the New Mexico Institute of Mining and Technology). The internal clocks of the seismographs were synchronized to each other daily and the instruments were programmed to record twelve 2-min records during each hour at a sample rate of 200 Hz. The 45 seismographs were spaced at 20-m intervals along 900-m segments of our 16-km-long profile. We advanced the transect with a roll-along procedure, moving 15 seismographs forward after at least 10 min of data had been acquired. Repeating the roll-along allowed us to complete a 16-km transect in 9 days.

The array data were processed according to Louie's (2001) refraction microtremor analysis to produce a shear-wave velocity versus depth profile for each 15-instrument, 300-m segment. Figure 3 shows an example of the seismic records from a 900-m-long array east of downtown Reno, and also a slowness-frequency spectrum from a 300-m array downtown. We picked Rayleigh dispersion points along a minimum-velocity envelope of the energy in the slowness-frequency image. Typical dispersion runs from small slow-

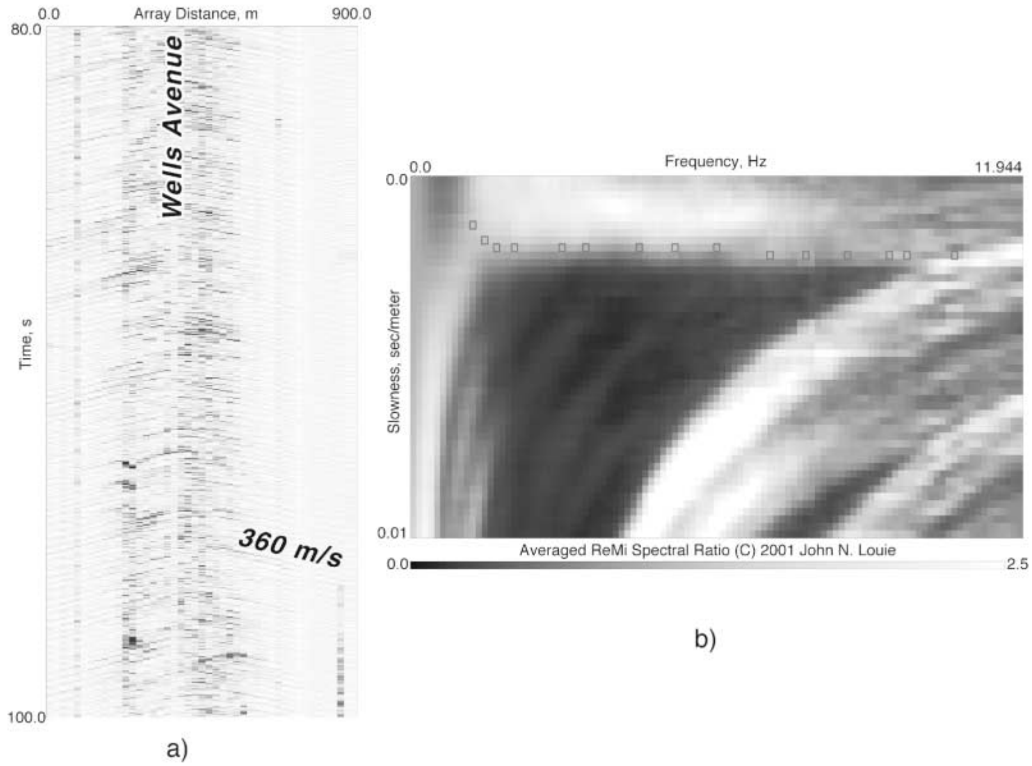

Figure 3. (a) Twenty seconds of example seismic data from a 900-m-long east–west array of 45 recorders crossing Wells Avenue in Reno (at transect distance 6.1 km). Note the prominent waves radiating east and west from heavy traffic at 360 m/sec. (b) Example slowness-frequency (*p-f*) spectrum, in the manner of Louie (2001), for a 300-m-long array extending west from Virginia Street in downtown Reno, at 4.9 km transect distance. Increased spectral ratio, defined as the ratio of the spectral power at a particular slowness and frequency over the average spectral power for all slownesses at that frequency, is represented as lighter parts of the *p-f* image. Square symbols mark the fundamental-mode Rayleigh wave-phase velocity dispersion picks for this array. With a slowness range on the vertical axis of 0–0.01 sec/meter, this *p-f* spectrum analyzes for apparent velocities (in the west–east direction of this linear array) of 100 m/sec at the bottom edge of the plot to infinite velocity at the top edge.

ness values at low frequencies, down to the right toward larger slowness values at higher frequencies (Fig. 3, right). The picks for this array run from frequencies of 1.16 to 10.55 Hz.

We interactively forward-modeled the fundamental-mode Rayleigh dispersion curve for each 300-m segment to obtain a shear-wave velocity versus depth relationship. As described by Louie (2001), the interactive forward-modeling process included analyses of the depth to which shear-wave velocities can be resolved from the Rayleigh dispersion picks. We computed Vs30 by arithmetically averaging slownesses to 30 m depth (by slowness to preserve bulk travel time). The total time to measure one location, from array layout to velocity modeling, can be as little as 2 hr.

Results

The values of Vs30 we obtained from the 55 microtremor arrays deployed along our transect are given in Figure 4. The shear-wave velocity section along the transect, assembled and smoothed from the 55 velocity–depth profiles, is contoured in Figure 5. Along the transect, we achieved control on modeled velocities in the 55 profiles to depths between 100 and 300 m. As seen in Figure 4, the values of Vs30 east of the airport, in the 1997 floodplain, are on the NEHRP-C/D boundary. Vs30 values transition westward to a C classification for downtown Reno. Velocities rise west of downtown, toward Tertiary sandstones and diatomites outcropping within several hundred meters of the transect.

Vs30 measurements become relatively high just east of where the transect crosses West McCarran Boulevard (1.6-km transect distance on Figs. 1 and 4). This segment, identified as Qto on the basis of the geologic map, would previously have been classified as NEHRP-C/D. We found that location to have a Vs30 of 849 m/sec, classifying it instead as NEHRP-B. The velocity section of Figure 5 shows that, even after lateral smoothing, high-velocity contours (600 m/sec and above) come very close to the surface at this location. Abbott and Louie (2000) proposed from gravity and well data that higher-density, more lithified Tertiary sandstones and diatomites (compared with young Quaternary sediments) are buried at about 200 m depth east of downtown Reno, but shallow and crop out frequently west of downtown. The 600 m/sec velocity contour in Figure 5 may be tracing the top of the Tertiary sediments in this cross section.

The correlation between adjacent measurements is good, as Fig. 4 shows, for example, in the multipoint Vs30 gradient between 0- and 1.6-km distance. A separate measurement of Vs30 on the University of Nevada–Reno campus (see location in Fig. 1) was 360 m/sec in contrast to the corresponding transect value at the 4.9-km distance of 507 m/sec (Fig. 4). We interpret this difference to be caused by greater stiffness in the gravelly sediments adjacent to the Truckee River, contrasting against the lesser stiffness of the deeply weathered clay-rich soils found on terraces above the river, as on the campus.

To assess the relationship between our measured values of Vs30 and mapped geologic formation or soil type, we consulted local geologic maps (Bonham and Bingler, 1973; Bell and Bonham, 1987) and soil maps (Nevada Bureau of Mines and Geology [NBMG], 1973; U.S. Department of Agriculture Soil Conservation Service [USDA-SCS], 1978) along the transect. A geologic formation type and a soil type were assigned to each transect segment. The measured values of Vs30 from each segment are plotted for each geologic

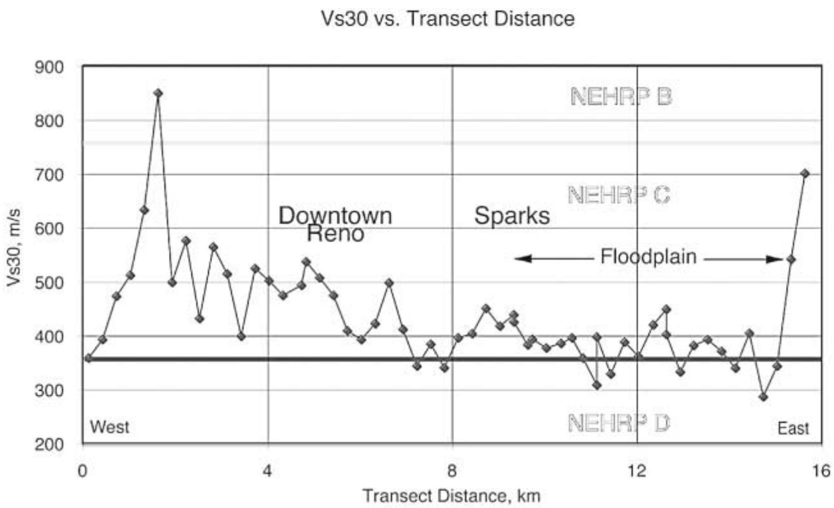

Figure 4. Our measured values of Vs30 for 55 points along the Reno transect. Vs30 values are slowness-averaged from 55 modeled velocity–depth profiles. Sites with Vs30 greater than 760 m/sec are classified as NEHRP B; between 760 and 360 m/sec, as NEHRP C; and 360 to 150 m/sec, as NEHRP D (plot extends only to 200 m/sec). Refer to Figure 1 for geographical references for transect distances.

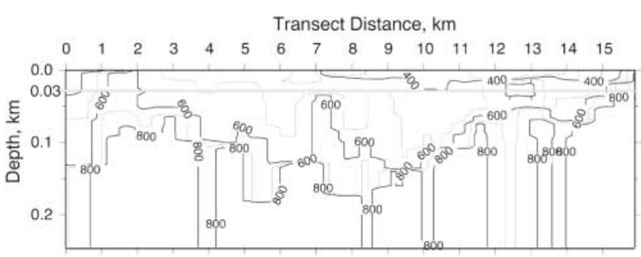

Figure 5. Shear-wave-velocity section assembled from 55 velocity–depth profiles that model the dispersion curves derived from all fifty-five, 300-m microtremor array segments. Velocities deeper than 200 m are least constrained by the dispersion data and thus vary widely between the segments. To prevent this unconstrained variation from dominating the contour plot, the velocities were slowness-smoothed horizontally with a 300-m moving window before contouring. Shallower velocities show more stability but are also horizontally smoothed for this plot. This section has 20 times vertical exaggeration. Values contoured are in m/sec. Contour interval is 100 m/sec between 300 and 800 m/sec. (Velocities not between 300 and 800 m/sec are not contoured.) Refer to Figure 1 for geographical references for transect distances.

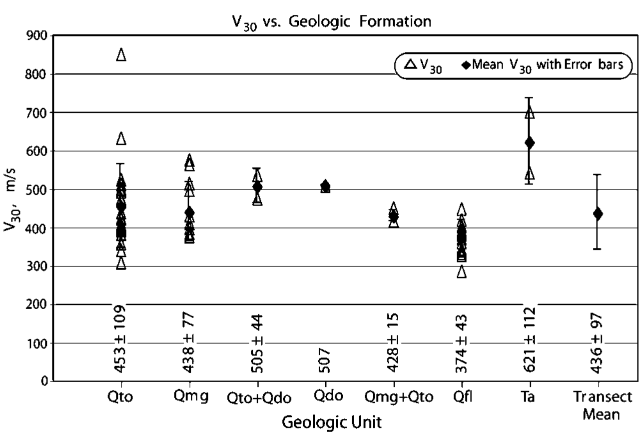

Figure 6. Measured values of Vs30 for each geologic formation type sampled by our transect (Table 1). Geology was was drawn from the specific local classifications of Bell and Bonham (1987) and Bonham and Bingler (1973), which differ from the regional units broken out for all of Washoe county by the NBMG digital geologic map (2000). The velocity average and standard deviation for each formation are indicated. No deviation is shown for the formation sampled only once. Units are combined where an array measurement overlaps both.

Table 1
Reno Transect Geologic Map Classifications from Bell and Bonham (1987) and Bonham and Bingler (1973)

Geologic Units Symbol	Description
Ta	**Alta Formation:** pyroxene, pyroxene hornblende, and hornblende andesite flows; debris flows; and pyroclastic flows.
Qfl	**Floodplain deposits of the Truckee River:** light grey to dark grey-brown silt, sandy silt, and clayey silt with local lenses of well-rounded pebble to cobble gravel; derived from mainstream and overbank deposition of the Truckee River; includes oxbow lakes and old channels. Locally contains peat layers.
Qto	**Tahoe Outwash:** gray, sandy, cobble to boulder gravel with lenses of light brown to light grey medium sand and light grey clayey silt. Gravel and sand are well stratified with fluvial crossbedding and are moderately to poorly sorted. Gravel composed dominantly of well-rounded volcanic and granitic clasts; granitic boulders as much as 3 m in diameter occur in Truckee meadows and giant Mzv blocks as much as 10 m in diameter occur at Mustang. Deposits typically occur on terrace remnants and underlie much of Truckee meadows at shallow depths. Soil typically has strongly developed argillic B horizon 30–60 cm thick.
Qdo	**Donner Lake Outwash:** grey to brown, sandy cobble to boulder gravel composed dominantly of well-rounded volcanic and granitic clasts. At Mustang deposit, is deeply channeled and contains giant Mzv boulders 3 m or more in diameter. Soil typically has a strongly developed argillic B horizor 60–100 cm thick underlain by a siliceous and calcareous duripan about 60 cm thick.
Qmg	**Mainstream Gravel:** sandy cobble gravel confined to the present Truckee River floodplain.

This very local classification differs from the regional unit classifications given in the county-wide digital geologic maps (NBMG, 2000), shown on Figure 1.

Table 2
Reno Transect Soil Map Classifications from NBMG (1973) and USDA (1978)

Symbol	Description
450	**Cave variant very cobbly, very fine sandy loam, 4%–30% slopes**
451	**Hyloc-Inster association**
590	**Springmeyer stony loam 0%–2% slopes:** very deep soils with moderately coarse to moderately fine textured subsoils on alluvial fans, terraces, and scarps.
591	**Springmeyer stony loam 2%–4% slopes:** very deep soils with moderately coarse to moderately fine textured subsoils on alluvial fans, terraces, and scarps.
661	**Qest bouldery sandy loam, 2%–8% slopes:** very deep soils with moderately coarse to moderately fine textured subsoils on alluvial fans, terraces, and scarps.
669	**Qest gravelly sandy loam, 0%–2% slopes:** very deep soils with moderately coarse to moderately fine textured subsoils on alluvial fans, terraces, and scarps.
705	**Poor and poorly drained soils on floodplains and low terraces:** Jame Canyon very fine sandy loam, overwash, 0%–2% slopes.
800	**Truckee loam:** poor and poorly drained soils on flood plains and low terraces.
802	**Truckee loam, strongly saline:** poor and poorly drained soils on floodplains and low terraces.
810	**Rose Creek fine sandy loam:** poor and poorly drained soils on floodplains and low terraces.
812	**Rose Creek loamy fine sand:** poor and poorly drained soils on floodplains and low terraces.
813	**Rose Creek fine sand loam:** poor and poorly drained soils on floodplains and low terraces.
991	**Madeland:** Cut and fill areas of admixtures of soil and nonsoil materials.

formation in Figure 6, and Table 1 describes the formations. The measured values of Vs30 for each soil type at each segment are plotted in Figure 7, and Table 2 describes the soil types.

Fifty-three of our locations were on the geologically youngest and most active fluvial units (in contrast to nearby older alluvium, and Tertiary sandstones and volcanics, Fig. 1). However, these sites showed Vs30 values ranging from 286 m/sec (NEHRP-D) to 849 m/sec (NEHRP-B). This large range of our Vs30 measurements on these units suggests that the presence of young, active alluvium is not a predictor of low shear velocities (NEHRP classes C/D or D).

Following the suggestion in Figure 5 that the depth of the top of Tertiary sediments may be appearing in our velocity results, we developed a simple model using the thickness of Quaternary alluvium from Figure 2 to attempt an independent prediction of Vs30 along the transect. A good fit to our transect data was obtained by choosing a value of 400 m/sec for the shear-wave velocity in Quaternary alluvium and 600 m/sec for the underlying Tertiary sandstone and diatomite. The value of Vs30 was computed as follows, by arithmetic averaging of slownesses:

$$\mathrm{Vs30} = \frac{30}{\frac{t_a}{400} + \frac{t_r}{600}}$$

where t_a is the thickness of alluvium ($\leq$30 m) and $t_r = (30 - t_a)$. The results from this simple model are compared with measured Vs30 values in Figure 8.

Discussion

Our transect is a first step toward the preparation of a map showing NEHRP classifications for the Reno basin based on local site-condition measurements. In advance of the transect measurements we had found it reasonable to infer classifications from the California map (Wills *et al.*, 2000) for regions near Reno having similar surface geologic features. We examined detailed California geologic maps (California Division of Mines and Geology [CDMG], 1958–1963) and chose three basins (Table 3) having formations that bear similarity to those on the Reno maps (Bonham and Bingler, 1973; Bell and Bonham, 1987). These basins are filled with young, active alluvium (Qal), lake deposits (Ql), and lake sand (Qs), units all classified by Wills *et al.* (2000) as NEHRP-D. With the exception of our two easternmost measurements, in competent Tertiary volcanic rock (**Tk** on

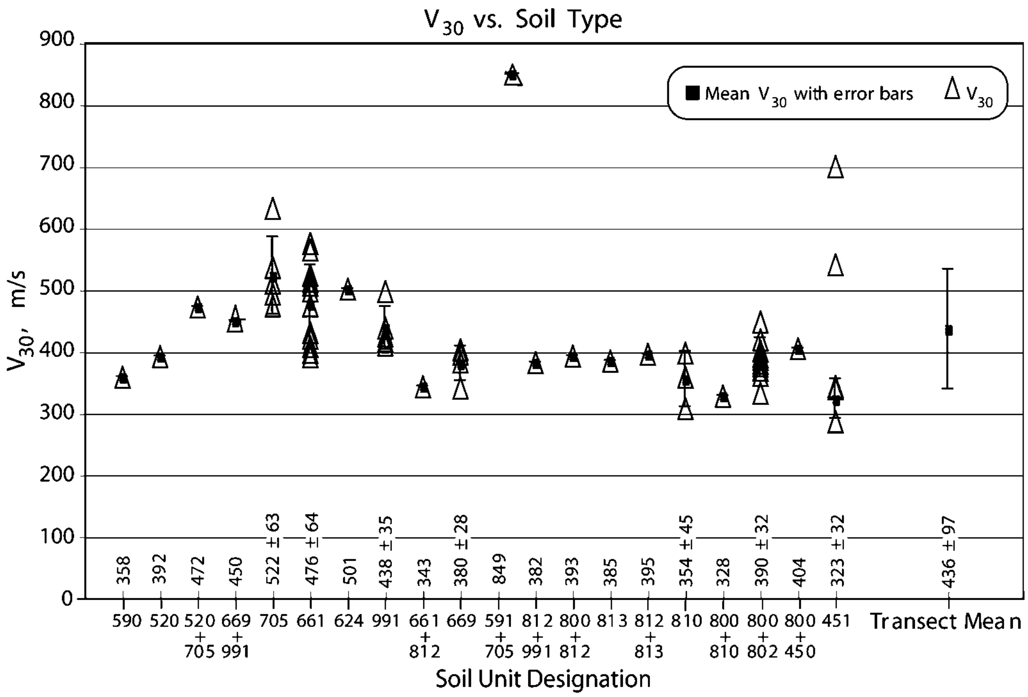

Figure 7. Measured values of Vs30 versus soil-type designations (Table 2). Most individual units have just one Vs30 measurement and thus no deviation. The velocity average and standard deviation of the other units are indicated. Units are combined where an array measurement overlaps both.

Fig. 1; **Ta** on Fig. 6 and in Table 1), all our Reno transect points are on similar recent, active Quaternary fluvial deposits and likewise would be classified NEHRP-D based on geologic mapping.

In Figure 6, we could find no predictive correlation between geologic map unit and our Vs30 measurements. The sole exception was where the geology was Tertiary volcanics (Ta) at the east end of the transect, which yielded higher velocities. In Figure 7, we can similarly identify that the variance in Vs30 within each of the several soil groups along the transect is greater than the differences in the average Vs30 between soil groups. Thus, we cannot predict Vs30 from the Reno soil maps. Analysis of the correlations in Figures 6 and 7 using the *F* statistic (Hoel, 1971) confirmed the lack of correlation.

Seeking any model with a better ability to predict Vs30 in this basin, we found that a simple model based on alluvium depth derived from gravity modeling yielded better predictions. Our assumed values of shear-wave velocity for Reno alluvium of 400 m/sec and soft rock of 600 m/sec are based on a fit to our transect measurements. All but six of 55 predicted values (89%) were within the nominal ± 20% accuracy of the refraction microtremor measurements, as illustrated in Figure 8.

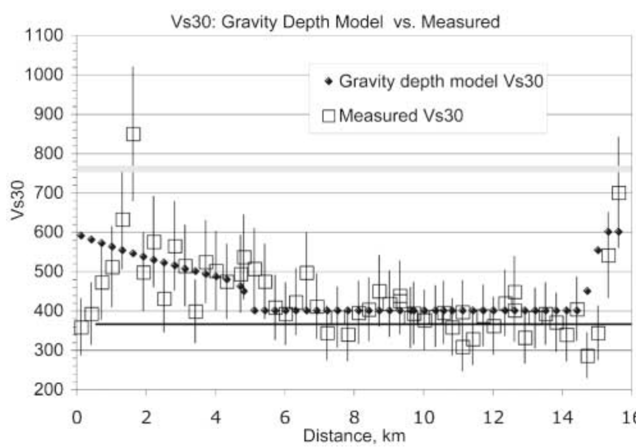

Figure 8. Vs30 according to an alluvium-depth model derived from a basin-gravity survey (Abbott and Louie, 2000) versus the measured values of Vs30 along the transect with ±20% error bars on the measurements.

Louie (2001) reports the ±20% velocity accuracy for the refraction microtremor method. To assess the standard deviation due to noise source and dispersion-picking differences for the individual Vs30 values, we made repeat array recordings at three locations along the transect. We independently processed and modeled the two sets of recordings from each repeated segment. The results are shown in Table 4. We concluded that the variability in the recorded sources of microtremor noise and in the picking and modeling process could be expected to contribute perhaps less than ± 10% error in Vs30.

Table 3
California Geologic Basins Chosen as Representative of the Reno Area Basin

Sheet	Map Date	Feature
Walker Lake	1963	Antelope Valley
Westwood	1960	Grizzly Valley
Chico	1962	Honey Lake

Table 4
Results of Repeated Determinations of Vs30 at Three Locations along the Transect

Distance	Vs30 Values	$Vs30_{ave}$	σ	$(\sigma/Vs30_{ave}) \times 100\%$	Approx. Difference, ±%
9.34	425, 438	431.5	9.19	2.1	1
11.14	397, 308	352.5	62.9	17.8	9
12.64	401, 448	424.5	33.2	7.8	4

Conclusions

We can, for the first time and with minimal effort, obtain a detailed shallow shear-wave velocity transect across an entire urban basin. The plot in Figure 4 shows measured Vs30 values above 360 m/sec for 82% of the transect, forty-five of fifty-five 300-m transect segments. Classification of most of the Reno area basin as NEHRP-D based on geologic mapping is therefore unwarranted.

We have also shown that gravity-derived alluvium-depth modeling can be combined with refraction microtremor Vs30 measurements to yield good shear-wave velocity predictions for the Reno basin. Unlike the Los Angeles basin, the Reno basin's greatest depths have stiffer, Tertiary sediments underlying the surface. Weaker soils appear to occur east of downtown Reno in the floodplain of the Truckee River.

Although most of our locations were on the geologically youngest and most active fluvial units, these sites showed Vs30 values ranging from NEHRP hazard class D up to class B. Mapped geologic and soil units are not accurate predictors of Vs30 measurements in this urban area.

Acknowledgments

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More information on urban shear-wave velocity transects can be found at www.seismo.unr.edu/hazsurv.

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