11-2008

Characterizing Anomalous Ground for Engineering Applications Using Surface-Based Seismic Methods

Barbara Luke
University of Nevada, Las Vegas

Wanda Taylor
University of Nevada, Las Vegas

Carlos Calderon-Macias
Ion-GX Technology

Xiaohui Jin
EBA Engineering

Helena Murvosh
University of Nevada, Las Vegas

See next page for additional authors

Authors
Barbara Luke, Wanda Taylor, Carlos Calderon-Macias, Xiaohui Jin, Helena Murvosh, and Jeff Wagoner

Characterizing anomalous ground for engineering applications using surface-based seismic methods

BARBARA LUKE and WANDA TAYLOR, University of Nevada–Las Vegas, USA
CARLOS CALDERÓN-MACÍAS, Ion-GX Technology, Houston, USA
XIAOHUI JIN, EBA Engineering, Baltimore, USA
HELENA MURVOSH, Stanley Consultants, Las Vegas, USA
JEFF WAGONER, Lawrence Livermore National Laboratory, USA

Shallow seismics are in demand today in tectonically active regions to characterize and classify sites for earthquake response studies. The surface-based seismic methods are the most widely used for this purpose. In developed areas, the passive-source methods, also known as microtremor methods, are popular because of their efficiency and because the available frequency content is appropriate to determine an average shear-wave velocity for the upper 30 m. This information is required by the International Building Code, which is used by many municipalities in the US and elsewhere.

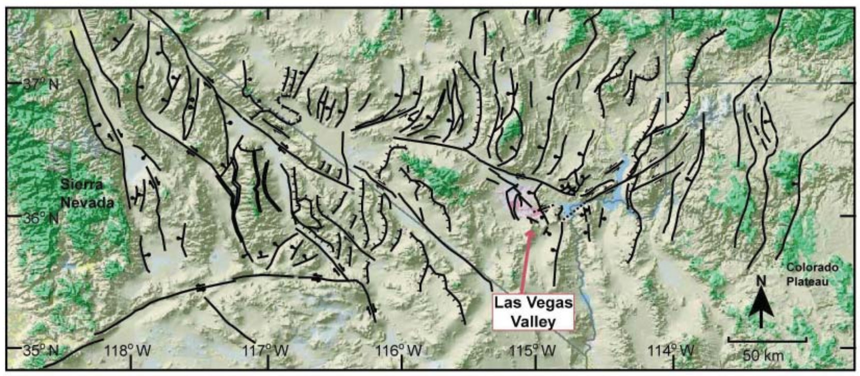

Figure 1. *Generalized locations of Quaternary fault scarps in the vicinity of Las Vegas. Fault locations are from* www.earthquake.usgs.gov/regional/qfaults/.

Earthquake-induced ground shaking is profoundly influenced by shallow shear-wave velocity structure due to the close relationship between the shear-wave velocity and the small-strain shear modulus. Site-specific earthquake ground motion analysis requires detailed shear-wave velocity profiles. For this, active-source methods are needed. The active-source method might be used to resolve shallow, high-frequency content and then merged with passive-source data for deeper resolution, or the survey to depth might be conducted using a high-energy source, such as a vibroseis.

We illustrate the use of surface-wave methods to build a shallow, 3D shear-wave velocity map for the Las Vegas Valley in Nevada. The Las Vegas Valley is fault-bounded and partially filled by sediments from the Oligocene age and younger. The valley is home to more than two million people, and its earthquake risk is considered moderate. The level of risk is continually reassessed as new data are collected (Figure 1).

The consequences of a severe earthquake in Las Vegas are potentially disastrous. For example, researchers with the Nevada Bureau of Mines and Geology, conducting a loss-estimation analysis using the FEMA software HAZUS, considered a magnitude 6.6 event on the Frenchman Mountain fault, which traverses the valley. They projected as many as 4000 casualties, 60 000 buildings suffering major damage and US$17.7 billion in economic losses (*www.nbmg.unr.edu/dox/of061/of061.htm*).

The shallow velocity map will be used directly in planning and also as input to site response analyses, to investigate spectral characteristics of credible earthquake ground motions, and to study how the response can vary across the valley.

SASW and MASW are two widely known test methods used to build shear-wave velocity profiles. The methods differ in the development and definition of the dispersion curves (velocity as a function of frequency or wavelength). Both methods have been shown to produce excellent results for sites where lateral heterogeneity is small and velocities increase gradually with depth. Building shear-wave velocity profiles becomes challenging when there is conflict between the complexity of the site response and the necessary simplicity of the theoretical model.

Processing surface-wave data from Las Vegas is challenging because the shallow subsurface is particularly heterogeneous. The valley sediments are very thick alluvial sequences ranging from clay to sand to gravel and boulders. Sediment sources include limestones, sandstones, and volcanic rocks. Depth to the Paleozoic basement has been estimated to be as much as 5 km, through combined gravity and seismic reflection interpretation by Vicki Langenheim and others of the U.S. Geological Survey. The depth to what engineers consider to be bedrock—lithified media of significant stiffness—is important for site-response modeling. This depth remains poorly constrained. As a further complication, the valley sediments are overprinted with secondary deposition of rock-hard calcium carbonates. These "caliche" lenses can be so indurated that they require explosives and other extreme measures to excavate. Once excavated, the blocks are favored as facing blocks for stout, earth-retaining walls or are pulverized to become aggregate. Carbonates can occur within sediments of any type, and the transition between uncemented (low velocity) and cemented media can be abrupt.

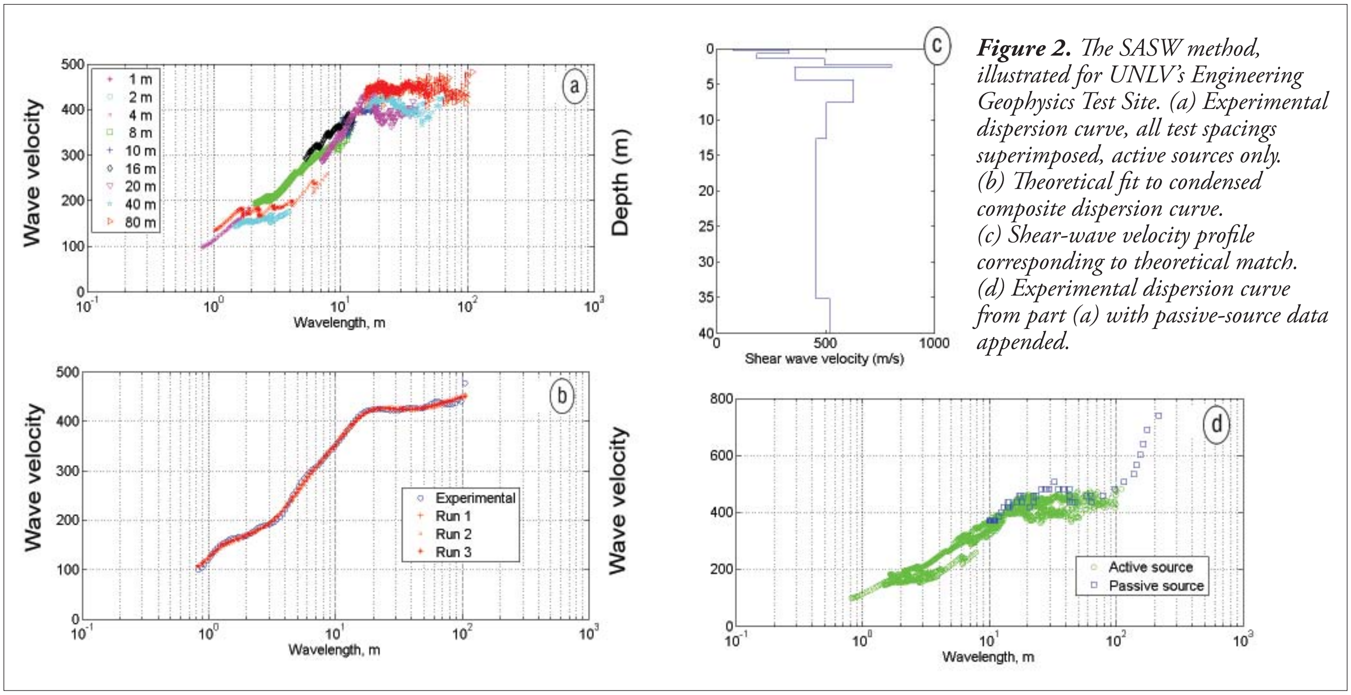

Figure 2. *The SASW method, illustrated for UNLV's Engineering Geophysics Test Site. (a) Experimental dispersion curve, all test spacings superimposed, active sources only. (b) Theoretical fit to condensed composite dispersion curve. (c) Shear-wave velocity profile corresponding to theoretical match. (d) Experimental dispersion curve from part (a) with passive-source data appended.*

Seismic methods

Spectral analysis of surface waves (SASW) was developed at the University of Texas at Austin by Kenneth Stokoe and his colleagues. This method uses a pair of vertical geophones placed in line with the active source. The test is repeated for different receiver separations (spacings). The source energy is successively increased as distance between receivers is increased; currently, we are using an instrumented sledgehammer for spacings from 1 to 8 m and then a "minivib" vibroseis for longer spacings that approach 100 m. In each test, the phase difference across the geophone pair is measured with respect to frequency. Wave velocity is easily derived from the phase difference and receiver spacing.

The measurements of phase velocity and frequency or wavelength from each receiver pair are merged to create an effective dispersion curve. This curve represents a summation of seismic energy, including all modes of surface-wave energy plus body waves and conversions. Data collected from a passive-energy source can be appended to extend the low-frequency end of the effective dispersion curve. The effective dispersion curve is smoothed and downsampled to become the target of a data-fitting inversion scheme in which a one-dimensional (1D) shear-wave velocity profile is derived. Multidimensional representations are possible by repeating the process at close offsets and merging outcomes. This process implies that the wavefields propagate locally in a 1D Earth.

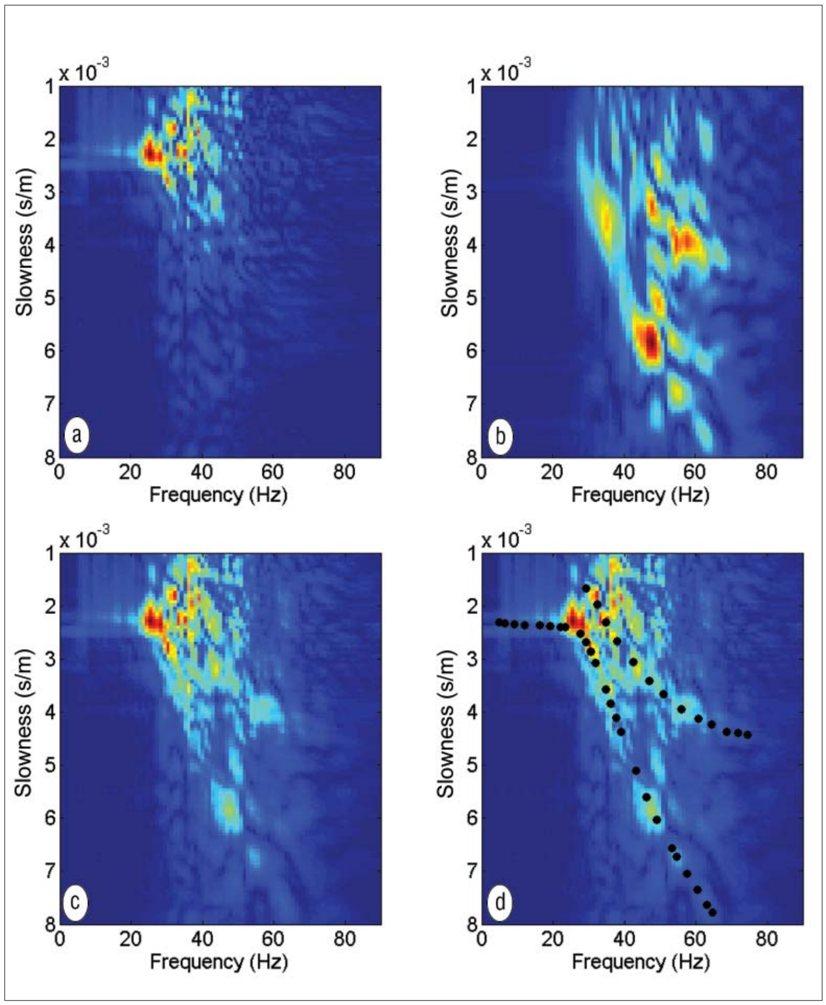

Figure 3. *Dispersion curves from the MASW method, UNLV's test site: (a) minivib source; (b) hammer source; (c) merged data; (d) merged data with manual picks for two modes.*

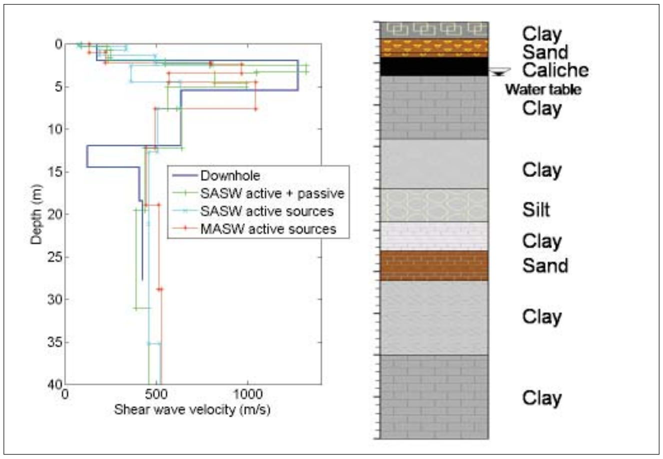

Figure 4. *Shear-wave velocity profiles for the UNLV test site from surface-wave measurements. Downhole seismic measurement results and borehole lithologic log provided for comparison.*

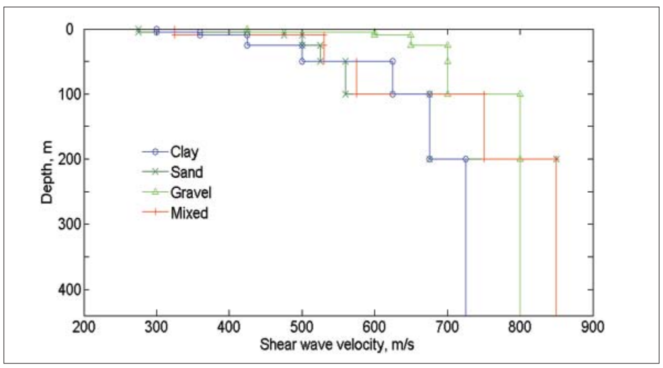

Figure 5. *Assigning shear-wave velocity to lithology as a function of depth. Assignments for caliche and bedrock are 1500 and 2600 m/s, respectively, irrespective of depth.*

Using only a sledgehammer for a source, a shear-wave velocity profile can be resolved to about 10 m in depth. By increasing energy output with a large weight-drop source or vibroseis, profiles can extend to 100 m deep or more.

Figure 2 illustrates processes for building a shear-wave velocity profile for UNLV Engineering Geophysics Test Site in the mid-valley; more information is available at *www.ce.unlv.edu/egl/test-site*. Depth to Paleozoic bedrock is approximately 1 km, according to Langenheim's model. A borehole log to 30 m indicates primarily clay, with a cemented zone at 2.5–4 m. The water table is at the base of the cemented layer.

The SASW data were collected using an instrumented hammer for short spacings and a 2040-kg dropped weight source owned and operated by Utah State University for spacings to 80 m. The shear-wave velocity profile was resolved to about 30 m depth.

A passive-source data set using the refraction microtremor process, which was developed by John Louie at University of Nevada, Reno was also collected at the site. The dispersion data achieved from that measurement could be appended to the active-source data to extend the profile depth.

Multichannel analysis of surface waves (MASW), developed by Choon Park and colleagues at the Kansas Geological Survey, involves the surveying of multichannel data. Active- and passive-source data can be incorporated. The frequency-slowness (*f-s*) transform is employed to build overtone images of dispersion. The dispersion curve for fundamental and higher modes is picked from the overtone plot. At the Engineering Geophysics Test Site at UNLV, two MASW data sets were collected, one with a sledgehammer source and another with a minivib (Figure 3). Results of the two were combined to enhance spectral resolution. The fundamental mode and the first higher mode were interpreted manually from the *f-s* transformed data.

Inversion methods

Deriving a shear-wave velocity profile from interpreted dispersion curves involves fitting the observed measurements with a synthetically derived dispersion curve using an ad hoc forward-modeling method and a starting or reference shear-wave velocity model. The reference shear-wave velocity profile is updated with the linearized inversion method and/or a global optimization method such as simulated annealing. In the presence of strongly heterogeneous media, we have used the simulated annealing method to address potential nonuniqueness. The process is configured to solve for a background velocity profile that can be overprinted with anomalous layers. The background profile has a fixed-layer geometry, and the shear-wave velocity is allowed to vary within fixed ranges. Search parameters for the anomalous layers are depth, thickness, and shear-wave velocity. Search ranges are set using all independent information available. Linearized inversion follows.

Shear-wave velocity profiles developed from SASW and MASW are shown in Figure 4. For the SASW data, addition of the passive-source data allowed the shear-wave velocity profile to be extended to more than 50 m. The MASW data, combining hammer with vibroseis, permitted a similar depth range of resolution. For ground truth, a lithologic borehole log is available to 30 m, as are the results of a downhole shear test to the same depth. The shear-wave velocity profiles from

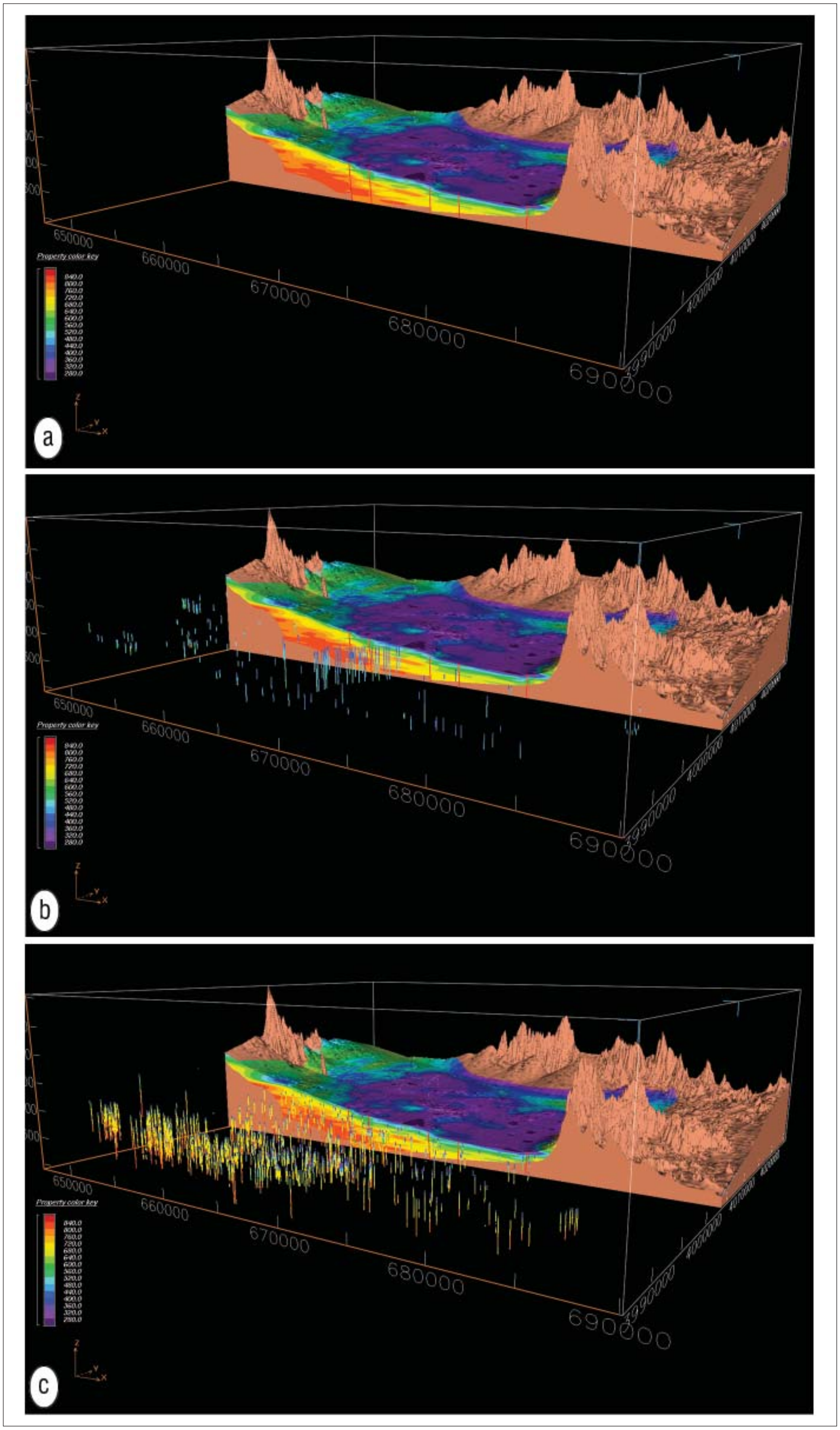

Figure 6. Preliminary 3D shallow shear-wave velocity model for Las Vegas Valley. Vertical exaggeration is 10 ×. Horizontal coordinates are UTM grid. Tick marks on vertical axis are in 200-m increments. Velocities range from 250 m/s (purple) to 900 m/s and over (red). (a) Velocities interpolated using lithology. (b) Velocity database feeding the 3D map. (c) Locations of lithologic well logs, which are color-coded to velocity according to Figure 5.

surface-wave measurements generally agree with one another. The vicinity of the cemented inclusion is least well resolved. The outcomes agree with numerical studies performed by the authors that showed that the depth of a shallow cemented layer (occurring, say, in the upper 10 m) is best resolved with respect to velocity and thickness, which tend to be underpredicted. Borehole logs and refraction data could then help guide the inversion.

In the inversion of the different data sets, different choices exist for the forward-modeling method used for data fitting. With the SASW data, although all energy types are represented in an effective dispersion curve, adopting a model limited to fundamental-mode Rayleigh energy was more successful (in terms of both dispersion curve fits and shear-wave velocity profile recovery) than a model that also accounted for higher-mode Rayleigh waves and body waves. For the MASW method, modeling the fundamental mode alone was more successful than when higher-mode energy was included. These outcomes are counter-intuitive. To explain the counter-intuitive results, we hypothesize that the experimental data sets are sufficiently complex that correct and complete interpretation of the field data requires more accuracy than might be possible. This is an area of active research: developing strategies that incorporate more complete modeling and inversion methods.

For the study site, all shear-wave velocity measurements yielded seismic site classification of "C, very dense soil and soft rock," whereas the classification based purely on lithology of this mostly clay site would have been "D, stiff soil."

Regional mapping

To date, we have collected detailed shear-wave velocity profiles at dozens of sites across the valley. Resolution depths range to 100 m and beyond. The effort to measure and interpret detailed shear-wave velocity profiles in the Las Vegas Valley is ongoing. In order to extend coverage across the valley, these profiles were augmented by more than 160 additional profiles filed with local government agencies for the purpose of seismic site classification for land development. Most of those additional profiles were generated using the refraction microtremor method.

The velocity data are interpolated across the valley using lithology, which is derived from a data set of nearly 1600 well logs. Depths of the well logs range from a few meters to more than a kilometer. The interpolation was accomplished by correlating shear-wave velocities in six lithologic categories and seven depth ranges (Figure 5).

A preliminary velocity map was assembled using the software EarthVision. The mapped region encompasses Quaternary and Pliocene sediments, terminating at the Miocene or Oligocene boundary, which is inferred from lithology. Fault scarps are also shown. Figure 6a shows surface velocities for the north half of the valley, and an east-west vertical slice. The density and distribution of velocity and lithologic logs used to create the 3D map are illustrated in Figure 6. In the topographic lows, where fine-grained sediments predominate in the shallow subsurface, shear-wave velocities of 300 m/s and less occur at the surface. Velocities remain below 700 m/s even at the Miocene/Oligocene boundary, hundreds of meters below. On the valley margins, recent alluvial deposits have higher velocities on the surface and at depth. The velocity map shows realistic offsets associated with the normal faults that cut through the valley.

Conclusions

Seismic surface-wave methods can be successful for developing meaningful velocity profiles, even in the near surface, which is notoriously complex. As site conditions increase in complexity, the use of independent prior information becomes ever more critical. Integration of surface-wave based methods, active and passive, with other geological, geophysical, and geotechnical information can improve both resolution of estimated shear-wave velocity profiles and depth of penetration.

Our current approach for developing a detailed shear-wave velocity model involves acquiring and processing MASW and SASW data from passive and active sources. We apply an interpretation scheme that incorporates a-priori information such as judicious search constraints based on geology. We also perform data fitting with an optimal forward modeling scheme.

Over recent years, widespread research has advanced the use of surface-wave methods such as SASW and MASW for site characterization. Still, there remains considerable opportunity for development to obtain better results with surface waves. One category is extending the applicability of these methods for mapping lateral heterogeneities such as tectonic faults, caliche lenses, fissures, cavities, facies boundaries, lost or forgotten utilities, and abandoned mines.

Regarding seismic response studies for the Las Vegas Valley, the next step is to finalize the velocity model and incorporate it into ground-shaking simulations. By doing so, we will be enhancing our understanding of earthquake hazards in a rapidly developing, major city that has a significant earthquake risk.

Suggested reading. "Inversion of seismic surface wave data to resolve complex profiles" by Luke and Calderón-Macías (*Journal of Geotechnical and Geoenvironmental Engineering*, 2007). "Interpreting complex layered systems by constrained optimization of surface wave data" by Luke et al. (SEG-Japan, 2006). "Estimation of near-surface shear-wave velocity by inversion of Rayleigh waves" by Xia et al. (Geophysics, 1999). "Characterization of geotechnical sites by SASW method" by Stokoe et al. (*Geophysical Characterization of Sites*, 1994). "Faster, better: Shear-wave velocity to 100 meters depth from refraction microtremor arrays" by Louie (*Bulletin of the Seismological Society of America*, 2001). "Multichannel analysis of surface waves (MASW)—Active and passive methods" by Park et al. (*TLE*, 2007). "Geophysical constraints on the location and geometry of the Las Vegas Valley Shear Zone, Nevada" by Langenheim et al. (*Tectonics,* 2001). TLE

Acknowledgments: Much of the research described here was supported by the U.S. Department of Energy and Lawrence Livermore National Laboratory. The authors thank Jonathan Carter and Ying Liu who are, respectively, current and former UNLV students; James Bay of Utah State University for the use of his dropped-weight seismic source; Eric Thompson of Tufts University for the raypath-tracing software we used for the downhole data; and Glenn Rix, Kenneth Stokoe, and Jose Roësset for sharing their computational models for surface-wave propagation.

Corresponding author: barbara.luke@unlv.edu