Passive near-surface seismic data where all else fails

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Geotechnical engineers remain busy assessing and rebuilding U.S. infrastructure, as part of the American Recovery and Reinvestment Act (ARRA) of 2009. Opportunities abound in the reconstruction of bridges and interstate highways, and also construction mass transit systems. Acquiring useful shallow (< 200 ft) seismic data in noisy urban conditions has always been difficult. The site conditions beneath bridges or in high-volume traffic corridors generally preclude acquisition of quality seismic data. Acquisition adjustments historically have not been practical and the results were seldom useful to the project engineer. But just because these sites are located in difficult urban settings does not mean geophysical imaging should be overlooked as a source of valuable information for engineering design or construction. With the advent of surface wavefield methods, particularly passive surface-wave recording, urban site conditions no longer pose the same limitations to all surface-based geophysics.

Near-surface seismic investigations along roadways or under bridges have traditionally been performed in existing borings drilled for geotechnical analysis. In part, this is because engineers are quite comfortable with crosshole and/or downhole shear-wave velocity (V_s) measurements for which ASTM standards (ASTM D-4428, 2007) exist. Engineers (the primary user group) are often unaware that surface-based seismic methods can map the vertical and horizontal distribution of V_s beneath noisy urban settings. Shear-wave velocities are valuable to the geotechnical engineer because the low-strain shear modulus (G_{max}) can be computed from the measured V_s and in-situ densities provided by laboratory tests. Two project examples presented in this article demonstrate the value near-surface geophysical investigations conducted in difficult urban settings can bring to geotechnical site assessment, design and construction

Methodology

Both urban sites discussed in this article include heavy traffic and other cultural noise sources, a shallow groundwater table, and a variable depth to the soil/rock interface. Therefore, to successfully provide useful engineering information about the subsurface, an out-of-the-box geophysical approach was required. Passive 1D V_s soundings to obtain V_s profiles to 100 ft for International Building Code requirements (IBC, 2006) have been common practice for almost a decade. These 1D V_s data are then used for site classification in seismic design and building retrofits. One of the passive 1D vertical seismic soundings methods is the passive surface-wave Refraction Microtremor (ReMi) method by SeisOpt (Pancha et. al., 2008, and Gamal and Pullammanappallil, 2011). The ReMi method utilizes standard receivers and engineering seismographs to take advantage of the dispersive nature of surface waves over the frequency range from less than 4 Hz to about 50 Hz. The method depends on the seismic characteristics of nearby ambient energy sources and restrained by the fundamental frequency of the geophones.

By deploying additional field instrumentation the 1D V_s sounding technique can be expanded to derive a cross section of V_s. As seismic reflection crews have done for years, the active spread is rolled along through a longer line of receivers. The approach determines the 2D lateral variability from a series of closely spaced 1D V_s soundings in a manner similar to the combination of (side-by-side) 1D time-domain electromagnetic (TDEM) soundings produce a 2D smooth model when plotted side-by-side. The instrument parameters and spacing of the 1D soundings can vary based on site conditions and project objectives.

Example 1

In Honolulu, Hawaii, a mass transit system has been planned for connecting the beaches in east Waikiki to west Waipahu. The factors driving this expansion include: (1) the intrastate system is at (or near) capacity for the volume of traffic in a growing metropolis; (2) the University of Hawaii bought a large tract of land near Waipahu (west Honolulu) to increase the campus size and school's capacity; and (3) the increasing volume of tourists commuting from the airport to Waikiki and the main attraction of Pearl Harbor. The Honolulu High-Capacity Transit Corridor Project (HHCTCP) began geotechnical investigations and site characterization in early 2007. The city of Honolulu specified that the location of the proposed transit system " ... is to be built along existing transportation right-of-ways." This requirement lead to the design of an elevated train system above the existing highways.

Geotechnical exploration began on the west end as construction was also planned to progress from west (Waipahu) to

Figure 1. *Forty-eight (4.5-Hz) geophones, spaced 10 ft apart along the guardrail of the eastbound lanes on Farrington Highway (Highway 93), west Waipahu, Hawaii. For crew safety, one lane of traffic was closed during data acquisition.*

east (Waikiki). Drill results indicated soft, saturated, unconsolidated soils, consisting primarily of coarse-grained sediments with lenses of fine-grained clay and silt, overlying basaltic bedrock. The initial phases of drilling surprised the design engineers with (1) the existence of soft soils, (2) a highly variable depth to bedrock, and (3) depth to bedrock far exceeding the predicted 100 ft. Drilling was terminated at a total depth (TD) of 177 ft below ground surface (bgs) at one location because of lack of drill rod. Geophysics was called upon to aid in the engineering design after several more borings encountered the highly variable soil composition and bedrock depths showed significant relief. The type of foundation elements and structural supports required for the elevated transit system depended on a detailed understanding of the stiffness of the soft soils, and the configuration of the soil/bedrock interface.

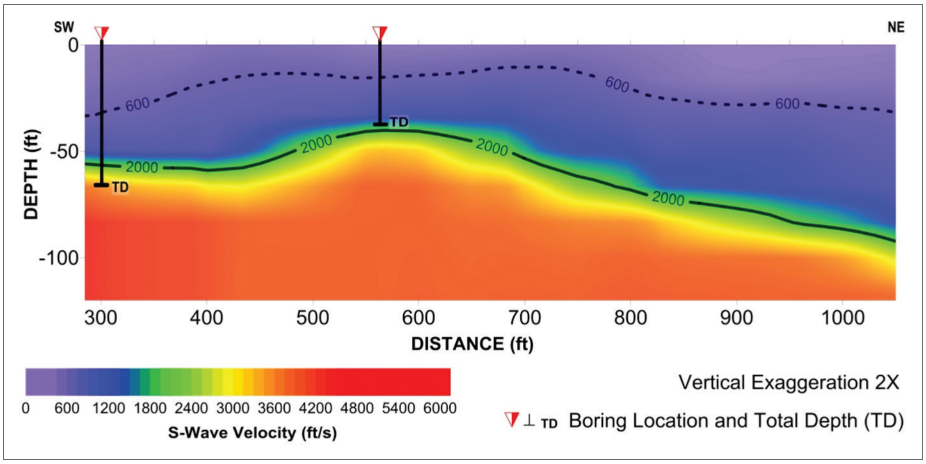

Figure 2. *2D ReMi* V_s *seismic section over blind test area.* V_s *contours at 600 and 2000 ft/s.*

Figure 3. *2D ReMi data acquisition at busy intersection along Farrington Highway. Note backhoe in background which was used to enhance inline ambient surface-wave energy. Quality data could be acquired under these extreme urban circumstances, but the health and safety of the crew (and geophysical equipment) was constantly monitored with the aid of police officers and traffic-control engineering.*

Because of the city's requirement to construct the HHCTCP on and near existing roadways, the 2D ReMi method was selected to assist characterizing the lateral variability of overburden soils and to determine the bedrock depth between and below the geotechnical borings. The geophysical project specified an initial blind-test phase to demonstrate that the passive surface-wave technique would satisfy the engineering objectives. Data acquisition for the test was constrained to the median of the Farrington (Highway 93) and King Kamehameha highways (Figure 1). The information provided for the blind test, was " ... saturated soils with an anticipated depth to bedrock of less than 100 feet." With saturation of the soils, busy highway conditions, and the possibility of velocity inversions within the sediments above bedrock, the passive surface-wave technique was uniquely compatible to the job requirements and site conditions. Traffic would be the primary source of ambient surface-wave energy to derive 1D V_s soundings spaced 40 ft apart for the test.

The blind test was performed near two borings and resulted in a 750-ft V_s profile (Figure 2). At both boring locations the depth to bedrock modeled using surface-wave analysis was within 5% of the depth to bedrock encountered in the borings. The blind test was determined successful and approval was given to investigate about 2.2 miles of roadway by project engineers.

The problems facing the design engineers were principally variable thicknesses of soft soils (less than 10 ft to greater than 25 ft) and a highly variable depth to bedrock (37–90 ft bgs) as seen in Figure 2). The velocity break points or contours identified on the figures were defined in conjunction with design engineers and project geologists to best represent soft soils (i.e., soils defined by $V_s < 600$ ft/s) in accordance with IBC criteria), dense soils (i.e., $600 < V_s < 2000$ ft/s), and an average V_s for the soil/bedrock contact of 2000 ft/s. If the variability in soil thickness and bedrock topography observed in the 750-ft blind test line was extrapolated across the 20-mile transit corridor of the proposed HHCTCP project, the high value of 2D seismic imaging becomes evident.

The overall 2.2-mile geophysical investigation was not contiguous because of river and flood-control canal crossings and traffic intersections that were too essential to traffic flow to even temporarily close one lane for acquisition of data. Additionally, based on drilling results, specific areas were interpreted to possess relatively uniform subsurface conditions, so no seismic data were collected. The field logistics required traffic control experts to develop work plans based on daily traffic patterns. Because of the traffic hazard, a police officer facilitated safety of the crew along most of the roadways. As this site demonstrates, urban geophysics settings can be much more dangerous to the health and safety of the crew than working in rugged outback field settings.

Figure 3 shows the field setup for acquisition of surface-wave data through a busy intersection. It was determined during on-site data processing that sideswipe from too much traffic noise caused high apparent velocities. To overcome this, an active source was placed inline with the receiver array. A backhoe can be seen in the background of Figure 3. No timing or triggering of the backhoe bucket hits were required for this passive seismic technique. The operator was simply instructed to create impacts with varying duration and strength. This proved to greatly enhance the data quality, particularly in areas of extreme high-volume traffic (i.e., intersections).

V_s data were obtained across one of the problem areas where the bedrock contact was not encountered during drilling because of equipment limitations (Figure 4). The V_s profile reveals that soil/bedrock interface in this area (beneath the area shown in Figure 3) is almost two-and-a-half times deeper than anticipated for this project. Additionally, the soft, saturated soils have a thickness of 40–50 ft (see 600 ft/s contour) and pose a significant risk of liquefaction during strong ground motion, and instability for lateral or vertical loads if not accounted for in foundation designs. Downhole shear-wave measurements were acquired in the borehole shown in Figure 4 at 2.5-ft increments from 0 to 57.5 ft. Downhole data revealed V_s values as low as 322 ft/s at 20-ft bgs, and velocities that increase from 583 ft/s at 47.5 ft to more than 1250 ft/s at 55 ft. These downhole V_s data correlate remarkably well with the 1D V_s ReMi data, extended to 2D profiling. Seismic profiles from this project (Figure 4) provided confidence in the method's ability to acquire accurate images of the subsurface in difficult urban conditions and results necessary to meet the objectives.

Approximately half (westernmost 6500 ft) of Phase 1 of the HHCTCP geophysical investigation is displayed in a compilation image (Figure 5). The east end of this phase ends just above Pearl Harbor. Each line segment was relatively flat. Data gaps represent rivers or canal crossings and intersections with heavy traffic. The compilation image clearly illustrates the potential geophysics has in difficult urban conditions to characterize changes in subsurface conditions that impact design of transportation projects. Determining that the soft soils vary in thickness from less than 10 ft to over 90 ft (i.e., west end of line segment 3), and the

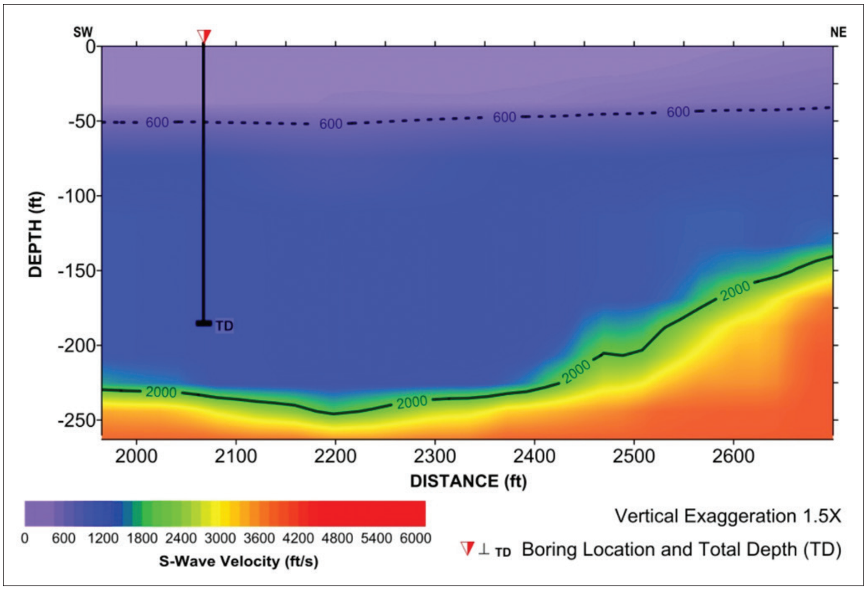

Figure 4. 2D ReMi V_s seismic section beneath area shown in Figure 3. Boring positioned at distance 2065 ft was the deepest geotechnical drill completed for the preconstruction geotechnical exploratory borings. V_s contours at 600 and 2000 ft/s.

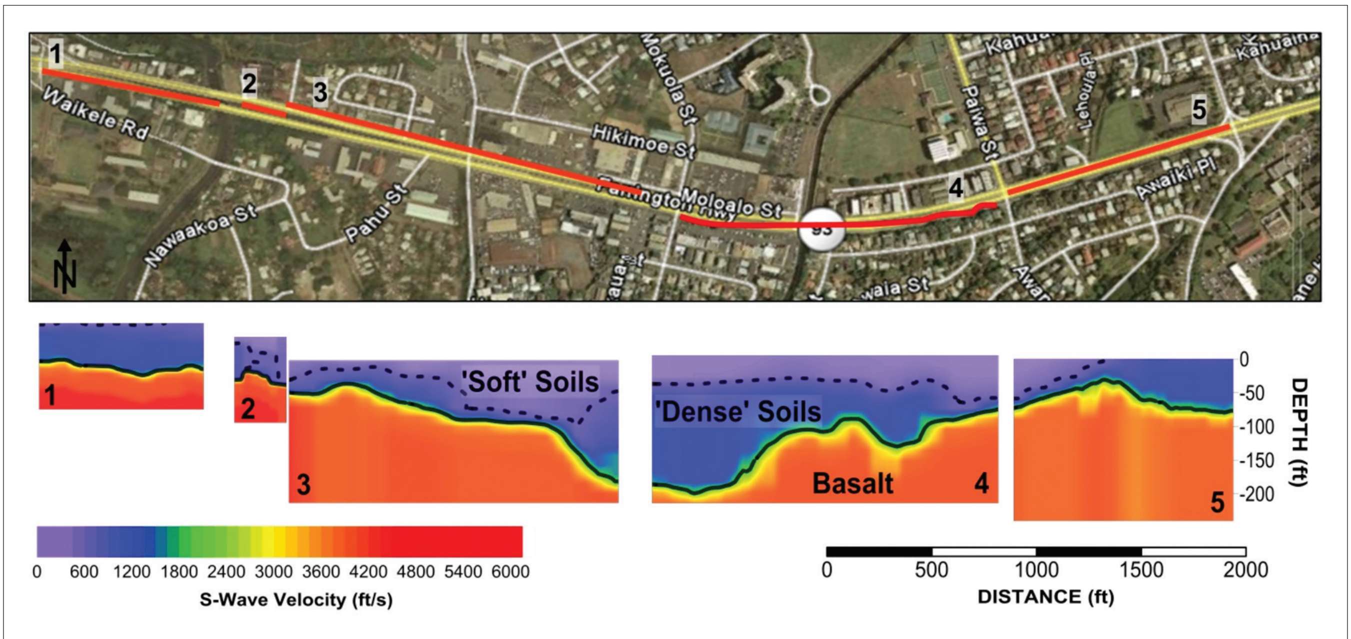

Figure 5. Compilation of a series of line segments for 2D ReMi V_s seismic sections along Farrington Highway. Plan view (top) presents position of each line segment and gaps in the data coverage. V_s contours at 600 and 2000 ft/s in the seismic profile.

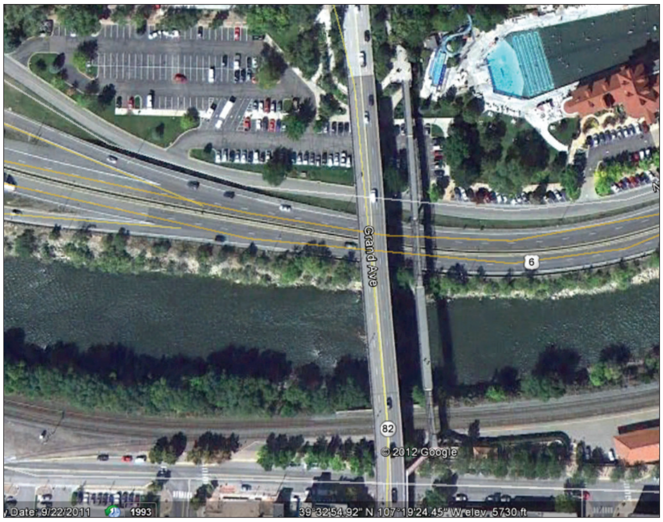

Figure 6. *Google Earth image for project 2. Grand Avenue Bridge (Highway 82 oriented NS) spans Interstate 70, the Colorado River, parking lots for the Glenwood Hot Springs pool facilities on the north bank of the river, and two sets of Amtrak railroad tracks on the south bank.*

Figure 7. *Seismic data acquisition along line 4, which is adjacent to the Grand Avenue concrete bridge piers, between the river and interstate. The Colorado River is immediately to the left (south); Interstate 70 is immediately to the right (north).*

configuration of a previously unknown bedrock channel in the middle of this area (i.e., line segment 4) with a passive surface-wave technique proved beneficial to the HHCTCP project team. Over the 5 miles ultimately investigated with this technique, bedrock was often closer to the surface than inferred from borings (sometimes less than 10 ft bgs) and the soft soils were intermittently present.

The variable thickness soils over basaltic bedrock, and the noisy urban setting precluded the use of standard refraction surveying methods and any EM or electrical method because of cultural interference at this site. Coastal tides likely provided low-frequency energy, possibly in the 2-Hz range, that allowed deep imaging of the soil/bedrock interface. The soil/bedrock interface appears distinct in the date examples shown, but there are areas where the bedrock was extremely weathered. In some locations, the soils had cemented into a coralline formation (cemented caliche-type soil deposit formed near coast lines) and the velocity images were more difficult to interpret. However, even in these areas, the data were useful to the designers, geotechnical engineers, and geologists. The quality of the shear-wave velocity distributions alone gave them the confidence to proceed with foundation design. Ultimately these geophysical data were correlated with ground-truth borehole/geotechnical information. A portion of the HHCTCP is currently under construction.

Example 2

Another challenging urban geophysical project was in Glenwood Springs, Colorado, where a problem with similar cultural considerations was attacked using the same field procedures and processing approach as in Hawaii. Glenwood Springs has an old four-lane bridge spanning the Colorado River (Figure 6). The Grand Avenue bridge connects the major thoroughfare of Interstate 70 with the city of Glenwood Springs. The bridge, being the only access (during winter months) to the city of Aspen and its ski areas, was proving incapable of handling the volume of traffic it was receiving. The Colorado Department of Transportation and the cities of Glenwood Springs and Aspen want to improve flow by widening and/or realigning the bridge to better match the volume of traffic coming off Interstate 70 and heading south.

Site conditions were similar to those described for the Honolulu project: extremely heavy traffic and an urban setting posing safety concerns for the geophysical crew and quality concerns for data. However, the near-surface geologic setting is considerably different than the previous example. Along the Colorado River are several terraces of high-energy, coarse-grained alluvial soils but these dense and unconsolidated soils have interbedded, indurated and discontinuous layers of tuffa and travertine. These lenticular deposits are formed by the flow of natural hot springs fluids emanating from karst-features in Mississippian-age limestone formations. The Leadville limestone crops out at the mouth of the Glenwood canyon just east of the hot springs pool facilities and is known for multiple natural hot springs in this area. The geothermal system, responsible for vapor caves and for over a century the famous Glenwood Hot Springs has been developed into a world-class resort and tourist attraction. The combination of a complex geologic setting and a geothermal system poses problems for engineers in designing appropriate foundation elements for the proposed new bridge.

There is one additional complexity beneath the project site. The indurated deposits (e.g., travertine) that exist intermittently within the alluvial soils act as an aquiclude to natural upward flow of geothermal water. These geothermal fluids are likely hydrologically connected to the pool's hot spring system. Because much of the city revenue base is derived from the Glenwood Hot Springs, the geothermal system is highly valued. On several occasions intrusive methods have been used to assess geotechnical properties of the subsurface and artesian geothermal fluid-flow conditions have been encountered where drill holes have penetrated travertine deposits. Therefore, in creating alternative bridge designs, constructors and geotechnical engineers not only must account for variable geologic conditions, but ultimately deal with a local geothermal system. The hydrologic conditions for this geothermal system are well protected by the owners and developers of the hot springs pool resort. Applying noninvasive geophysics in this urban setting makes perfect sense not only for the project team of geologists, engineers, hydrologists, but also for the significant sociopolitical contingent associated with the resort.

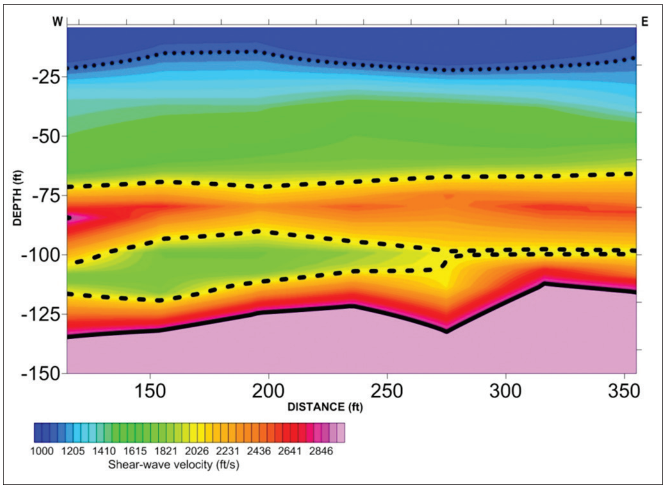

Figure 8. *2D ReMi V_s seismic section for line 1 where no geotechnical drill hole information was available along line. V_s contour lines drawn at 1100 ft/s (dotted), 2000 ft/s (dashed), and 2900 ft/s (solid). Note the velocity inversion for softer alluvial soils beneath a layer of high-velocity material, interpreted as travertine deposits.*

Five independent 2D ReMi lines of varying length were placed through parking lots, along medians, adjacent to cement barriers for the interstate, and on both banks of the Colorado River. The objectives were to assess lateral continuity of the alluvial deposits, existence of interbedded travertine layers, and variability of the limestone bedrock depth for the purpose of aiding engineers to position a new bridge and design its foundation. Although the area is safe for field work, similar traffic conditions to the Honolulu project are present (Figure 7). The on-site safety concerns are clearly different when working less than 50 ft from tractor/trailers (Interstate 70) and/or trains than in more rural settings.

Data were acquired during winter months to lessen the impact on tourism, and also at night (in the parking areas) because of access constraints on resort property. Instrumentation was similar to that used in Hawaii, using a 10-ft geophone spacing, multiple 24-channel spreads to derive a 1D V_s sounding every 40 ft along each line. Each line length was based on site conditions, access, and area of interest for the proposed alternative bridge alignments and/or abutment positions. Using the 2D passive surface-wave method proved effective because there was never a problem recording sufficient ambient energy in this tight, congested, and busy urban setting.

Line 1 is the northernmost line acquired through the parking facilities just west of the Grand Avenue Bridge (Figure 8). The line 1 shear-wave velocity results reveal a velocity inversion at a depth of about 100 ft. That is one aspect of using surface-wave modeling that is often underappreciated; that is, a velocity inversion can successfully be imaged. More standard V_P or V_s refraction surveys would not have imaged the low-velocity layer located beneath the thin higher velocity layer at approximately 70 ft bgs. The only boring in the area, southwest of line 1, encountered a layer, thickness approximately 15 ft, of travertine at about 60 ft and limestone bedrock at about 90 ft bgs. The log does not have the accuracy of a high-quality geotechnical-type borehole log, but the lithologic description correlates with the 2D V_s high-velocity layer evident beneath line 1.

Combining the five 2D V_s profiles into a 3D perspective view allows a visual representation of the V_s distribution beneath the entire area investigated. The 2D V_s data are superimposed over the Google Earth image to show the position of V_s data relative to the urban cultural features. Lines 1 and 2 are extended westward beyond the exiting bridge abutment to assess

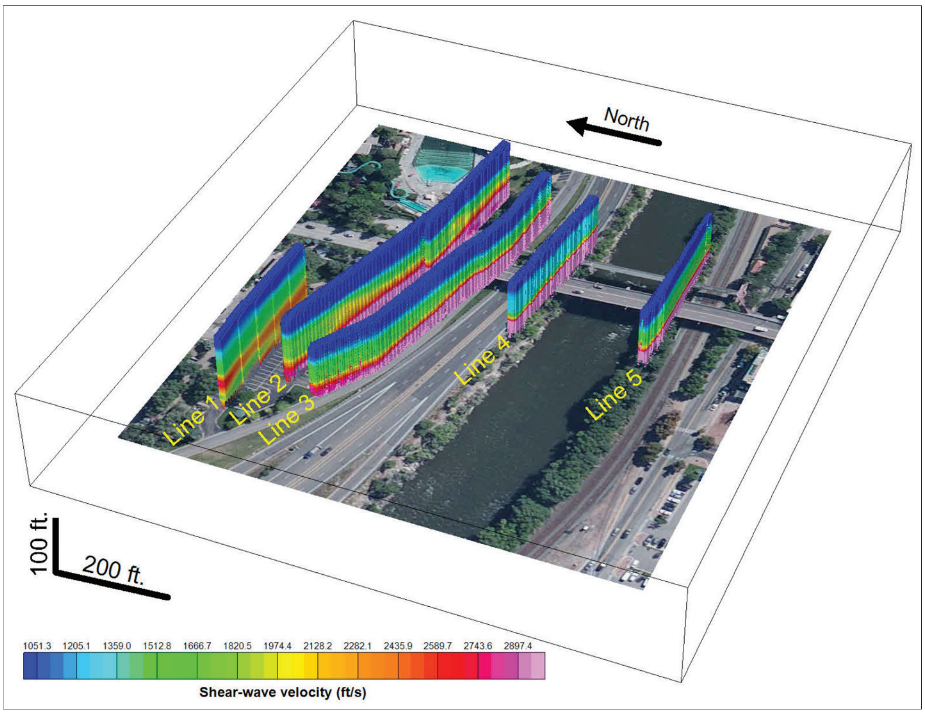

Figure 9. *2D ReMi results for five independent lines presented in a 3D perspective format, as viewed from above and to the northeast. Google Earth image is placed at the base of the 2D ReMi V_s profiles to illustrate positions of the data relative to the site features.*

Figure 10. *Acquisition of 3D seismic data above a retaining wall using a wireless seismic system. Without the need for seismic cables to be strung across a roadway, 2D lines and 3D grids can be easily deployed to achieve imaging in a safer manner—for both personnel and equipment.*

subsurface conditions for potential alternative alignments of the north bridge abutment. Shear-wave data visualization, where the bridge, interstate and river can be viewed with correct spatial positioning, is a useful tool for more easily integrating interpretations of all the geophysical data (Figure 9).

With little calibration or ground truth of these 2D V_s data, the following preliminary interpretations have been provided (Figure 9):

- The dark blue is interpreted as fill materials placed for the parking area, interstate and railroad corridors.
- The light blue is interpreted as loose young alluvial soils.
- Dense and older alluvium is interpreted to be represented by the green velocity layer(s).
- The travertine deposits are interpreted to be the yellow-to-orange layers.
- The Leadville limestone (or possibly the Beldon shale) is the highest velocity layer (shown as red to pink).

These shear-wave seismic data, when shown coregistered with the site features, provide a powerful image that should prove invaluable to the construction phase and demonstrates the effectiveness of urban geophysical investigations. The V_s data can be used for design and positioning of load-bearing foundations and alternative designs.

Conclusions and caveats

Two project examples have been used to illustrate the ability to acquire useful geophysical data, mainly shear-wave, in difficult urban settings. The approach to field work is unique but not without limitation. The SeisOpt ReMi method is an appropriate 1D V_s sounding technique. The usefulness increases with alternative field deployment and instrumentation design and allows successful expansion to 2D profiling. Key to effectively incorporating these results into engineering design and construction specifications is the understanding that the V_s results are determined using dispersive surface-wave analysis, and an awareness that the model inversion process can lead to nonunique solutions (i.e., equivalence modeling of layer thickness versus velocity). When calibrated with borehole data (e.g., geologic or geotechnical information), the shear-wave velocities can map layers and formations with confidence between and below drill holes. TLE

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