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Hammer Seismic Reflection Imaging in an Urban Environment

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Subsurface characterization within urban centers is critically important for city planners, municipalities, and engineers to estimate groundwater resources, track contaminants, assess earthquake or landslide hazards, and many other similar objectives. Improving geophysical imaging methods and results, while minimizing costs, provides greater opportunities for city/project planners and geophysicists alike to take advantage of the improved characterization afforded by the particular method. Seismic reflection results can provide hydrogeologic constraints for groundwater models, provide slip rate estimates for active faults, or simply map stratigraphy to provide target depth estimates. While many traditional urban seismic transects have included the use of vibroseis sources to improve reflection signals and attenuate cultural noise, low-cost and high-quality near-surface seismic reflection data can be obtained within an urban environment using impulsive sources at a variety of scales and at production rates that can significantly exceed those of swept sources.

Sledgehammers and hydraulically powered accelerated weight drops allow rapid acquisition rates through dense urban corridors where the objective is to image targets in the upper 1 km. In addition to the many extra steps often required to work in an urban area compared to more remote sites (e.g., complex permitting process, public awareness/education campaigns, damage to/interruption of roads/utilities), culturally noisy urban environments can provide additional challenges to producing high-quality seismic reflection results. Urban recording can be complicated by problems unique to this environment and can range from large-amplitude signals from vehicles and machinery to electrical signals within frequency bands of interest for near-surface targets. Acquisition methods designed to address both coherent and random noises include recording redundant, unstacked, unfiltered field records. Processing steps that improve data quality in this setting include diversity stacking to attenuate large-amplitude coherent (nonrepeatable) vehicle noise and subtraction of power-line signals via match filters to retain reflection signals near alternating current frequencies. These acquisition and processing approaches allow for rapid and low-cost data acquisition at the expense of moderately increased computing time and disk space. Here, I present acquisition and processing challenges that accompany urban seismic reflection surveys with examples using low-cost seismic sources where high-quality reflection images have been obtained along busy city streets during peak traffic hours. These examples are from earthquake hazards and groundwater studies and support the suggestion that seismic reflection imaging can provide a low-cost, high-quality component to many urban resource and hazard assessment studies.

Figure 1. *(a) Brady Flinchum operating the Boise State University hitch-mounted accelerated hammer source along a residential street in Reno, Nevada. A rubber mat is mounted below the plate to minimize road impact. (b) Trailer-mounted seismic source used to characterize groundwater aquifer through a high-traffic area in Boise, Idaho. (c) Portable slide hammer seismic source used to connect two weight drop seismic profiles along residential streets in Seattle, Washington.*

Rapid and flexible hammer seismic data

One of the challenges to acquiring quality seismic reflection data in an urban environment is the balance between an idealized profile for the geophysical target of interest and optimal seismic profile location. City streets or urban corridors may not extend across the geologic targets of interest. One benefit of small impulsive sources is an increased flexibility of survey location. Hitch-mounted weight drops or portable hammer sources allow surveys to be carried out along narrow property easements (e.g., bike paths, road shoulders, private property) or on soft ground where heavy trucks are not permitted (Figure 1). Operation of weight-drop sources may require a traffic control plan similar to vibroseis acquisition and a demonstration that the hammer will not impact city streets or utilities. Generally, standard street construction design will prevent damage from a large accelerated weight drop source with an appropriately designed striker plate. Compaction or damage of soft ground from a large hammer source and plate is generally not permanent. Because hydraulically driven accelerated hammers are impulsive, shot gathers can be acquired and recorded in a few seconds. In contrast, vibroseis records are generally acquired with long sweep and listen times that require tens of seconds to record a single sweep. As a result of more rapid acquisition, either a significantly greater number of shot gathers can be acquired per source location and/or production rates can be greatly improved when comparing impulsive sources to swept sources. In practice, 4–6 hammer shots per source location require approximately one minute to complete, resulting in 60 source points per hour. Assuming cables and geophones can

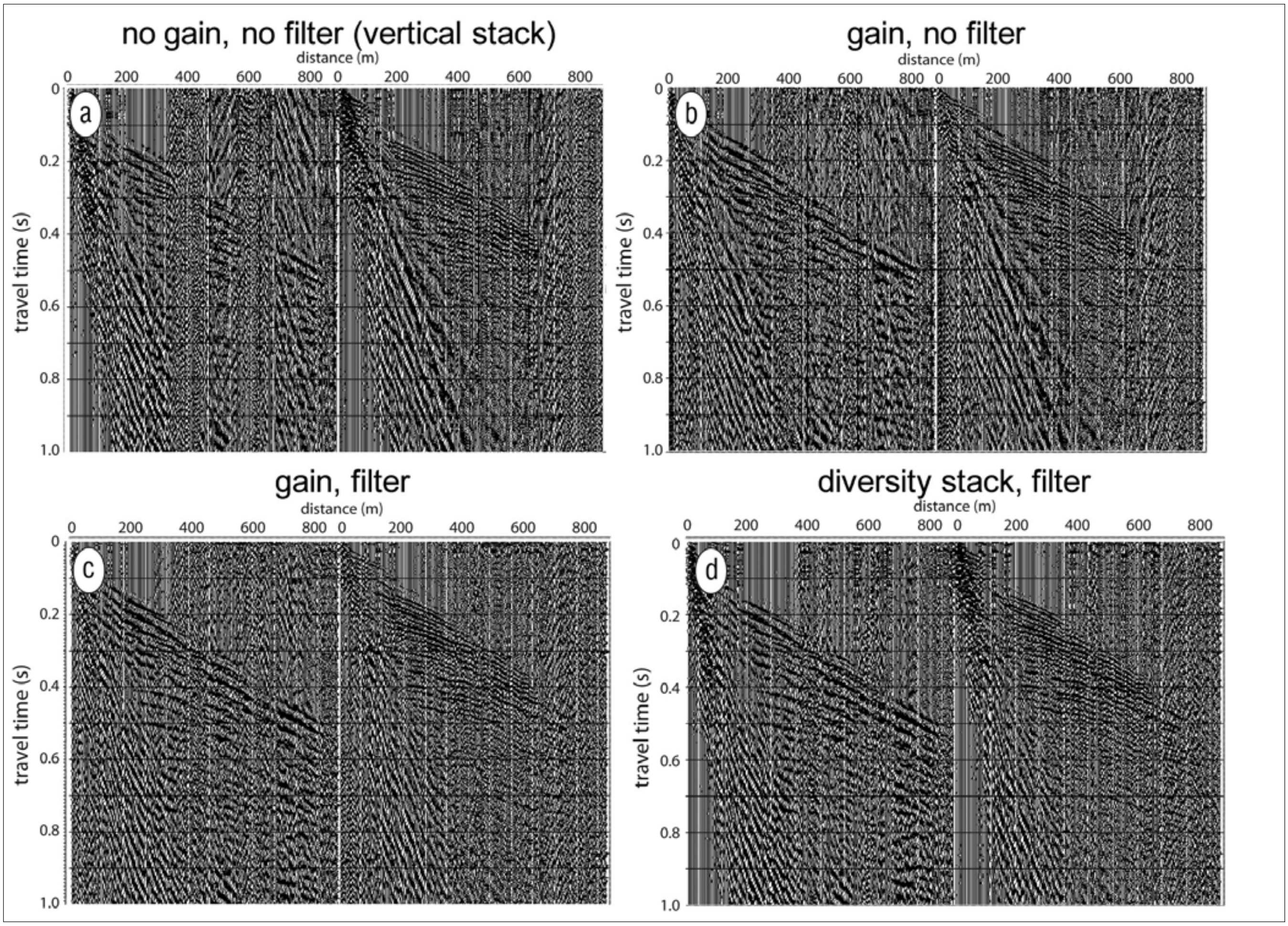

Figure 2. *Shot gathers along a city street with four summed gathers: (a) vertical stack with no gain or filter showing vehicle noise at large offsets; (b) AGC prior to vertical stack with no filter; (c) AGC and band-pass filter; and (d) diversity stack (scaled by the inverse of the power) and band-pass filter. Note the traffic noise identified on (a) is attenuated on (b) and (c), but best removed on (d). These data were acquired along a residential street in Seattle, Washington to identify and characterize active faults.*

be deployed as rapidly as source production rates, eight hours of shooting will yield 480 source positions per day. A typical CDP survey with 5-m spacing will then yield a production rate of nearly 2 km/d. Similar acquisition surveys using vibroseis sources have yielded approximately 1 km/d for the author.

Unlike frequency-controlled vibroseis sources, hammer sources can introduce larger-amplitude low-frequency signals that may not be desired for reflection imaging. Acquisition using higher natural-frequency geophones can reduce low-frequency surface-wave recording while retaining the higher-frequency signals. However, lower-frequency signals may dominate near-source channels and require either a surgical mute or filter to attenuate. Impulsive sources can produce reflected signals that are higher frequency than swept source capabilities (e.g., Bachrach and Nur, 1998); however, the variable amplitude with frequency response of impulsive sources often requires frequency balancing via shaping filters or deconvolution to broaden the signal response.

Nonstationary noise

Vehicle noise is likely the largest-amplitude noise source encountered in an urban environment. Although a large truck can saturate the dynamic range of modern seismographs, the traffic noise is often lower frequency than the reflection signal produced from many high-resolution seismic reflection surveys, and is nonstationary (Figure 2). This nonstationarity aspect is key to traffic noise attenuation. By recording many individual shots every few seconds, a standard vehicle traveling at residential speeds will move through the active recording spread. For example, a vehicle moving at 65 km/hr (18 m/s) will have moved 90 m in 5 s. Assuming 5 shots per station at 5 s between shots, the vehicle will have moved 450 m during the acquisition time for a given shot location. This distance is a typical spread length for a high-resolution seismic survey. By recording individual shots in the field, amplitude normalization or editing prior to stacking can significantly attenuate traffic noise. Generally, traffic will appear as high-amplitude, low-frequency, coherent noise with surface-wave velocities (Figure 2). With multiple shot records per station location to allow a vehicle to travel down the active spread, trace normalization prior to stacking will treat the nonstationary traffic noise as a random signal that can be attenuated with standard stacking procedures. A simple ap-

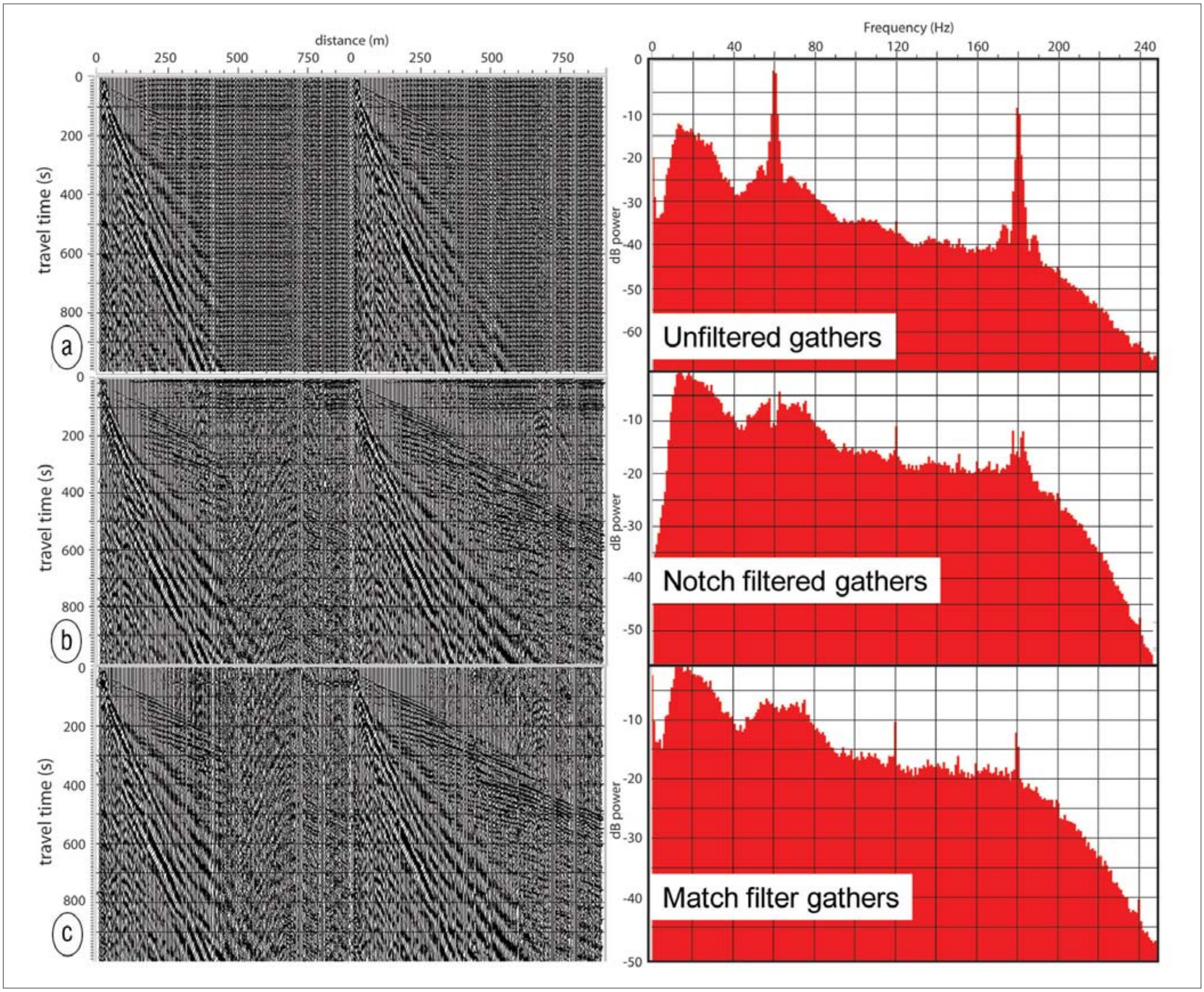

Figure 3. *(a) Unfiltered shot gather pairs acquired along residential street in Seattle, Washington with large overhead power lines. Frequency spectrum shows peak amplitudes at 60 and 180 Hz related to alternating current signals. (b) Notch filter response showing shot gathers remove much of the power-line noise. Filter artifacts appear above first arrivals and 60-Hz signals are removed. (c) Match filter design and subtracted from (a) to produce shot records where power-line signals are removed. Frequency spectrum is more consistent at 60 Hz where reflection signals remain in the shot record.*

proach is to scale each sample by the inverse of the power, or diversity stack. Using this stacking approach, large-amplitude traffic noise becomes a small-amplitude signal while repeatable reflection signals will remain intact. Figure 2 compares four individual hammer shots from a trailer-mounted weight drop (Figure 1) with signals to greater than 0.5 s and combined by: (a) a standard vertical-stack approach (sample averaging); (b) an amplitude gain control (AGC) prior to vertical stack with no band-pass filter; (c) AGC and band-pass filter prior to vertical stack; and (d) diversity stack and post-vertical-stack band-pass filter. Notice that the traffic noise identified on (a) is attenuated on (b) and (c), but best removed on (d). Figure 2d supports the suggestion that the best results are obtained by using a diversity stack approach to reducing the effects of large-amplitude nonstationary noise. In this example from Seattle, Washington, structures and stratigraphy were clearly imaged in the upper 1 km at a rate of nearly 2 km/d (e.g., Sherrod et al., 2008).

Attenuation of large-amplitude coherent noise in seismic reflection data has taken on new interest with simultaneous source acquisition methods now employed in the industry to increase production rates (e.g., Beasley, 2008). New processing methods can be directly applied to urban hammer seismic surveys. High-fold hammer data with standard processing steps can significantly improve data quality while improving production rates relative to vibroseis acquisition. The ability to acquire useful seismic data along the road shoulder of busy city streets comes at a cost of greater processing time and disk space to handle the larger data set. However, the ability to operate in urban centers, residential streets, and narrow easements during daylight hours can minimize community disruption and provide greater survey design flexibility.

Power-line noise

Power lines are difficult to avoid in urban areas. Power-line signal strength on a shot record can often be a function of ground saturation and surface materials, and can overwhelm the signal on a shot record (Figure 3). Generally, power-line noise appears as high-amplitude single-frequency signals (50 or 60 Hz). Related higher harmonic frequencies can often produce amplitudes of similar magnitude within the frequency range of the desired reflected signals. While notch filters will remove signals at a single frequency, this approach can have undesired filter effects, including removal of reflected energy within the notch band. Instead of notch filters to remove these signals, signal subtraction by designing a match filter is a more robust method to remove this noise (e.g., Butler and Russell, 1993; Xia and Miller, 2000). This method allows reflected signals to remain in the data set while removing the high-amplitude narrow-frequency, cyclic response of the power-line noise.

One more consequence to ignoring power-line signals or improperly removing power-line noise is the added difficulty of calculating a reliable residual static model. Application of residual statics with large-amplitude power-line signals retained in the data often results in alignment of out-of-phase power-line signals within common midpoint traces. Removal of power-line signals should be performed on individual unsummed traces to ensure the greatest efficiency of the match filter removing power-line signals.

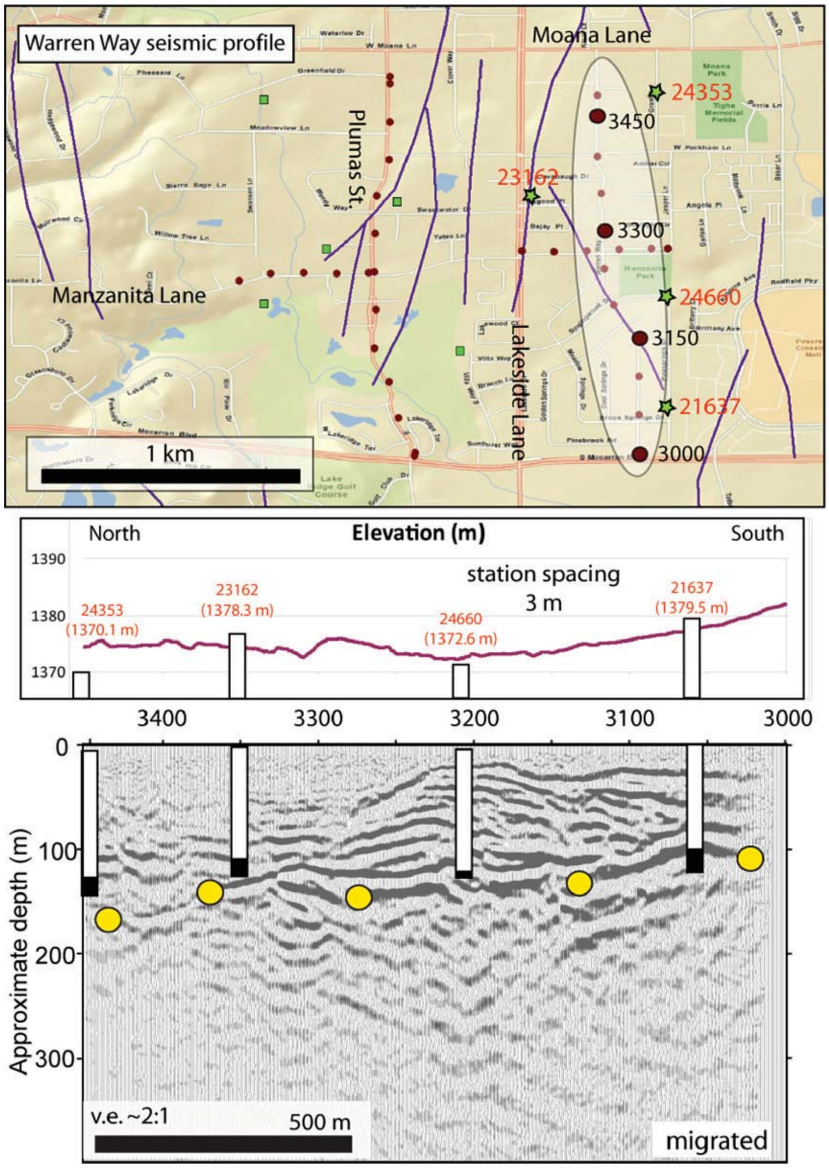

Figure 4. Map, elevation profile, and migrated/depth-converted hammer seismic section from Reno, Nevada. This 1.4-km, 3-m source- and receiver-spaced profile was acquired in a single day along a residential street. The bedrock surface was constrained by borehole information and seismic character. Reflections overlying the bedrock surface typify alluvial stratigraphy that dominates the Reno Basin.

Trigger timing errors

A contact closure or voltage-producing switch can trigger a seismograph when using a hammer source. These trigger signals are usually telemetered to the seismic recorder via ground wire or radio. Timing errors from contact closures can result from dirt on the strike plate (from dragging the plate on the ground) while hammer switches can produce spurious time breaks, variable pulse characteristics, and can vary sensitivity with increased usage. Radio triggers or trigger wires are sensitive to cultural noise interference (electric fences, power lines, etc.) that can also cause timing errors upward of a wavelength or more. As a consequence of the instability of time breaks, high-frequency data should not be stacked without addressing and estimating timing errors. Cross-correlation or residual static techniques can address these timing errors. Residual statics approaches for near-surface seismic studies have been summarized by Pugin and Pullan (2000).

Case studies

Reno, USA: active fault mapping. Five 120-channel hammer seismic profiles were acquired along residential streets to identify and characterize potentially active faults that cross the downtown Reno, Nevada area (Liberty, 2010). Figure 4 shows results from one profile that crosses a mapped fault at position 3150 along Warren Way in south Reno. This 1.4-km profile was acquired in a single day with a hitch-mounted

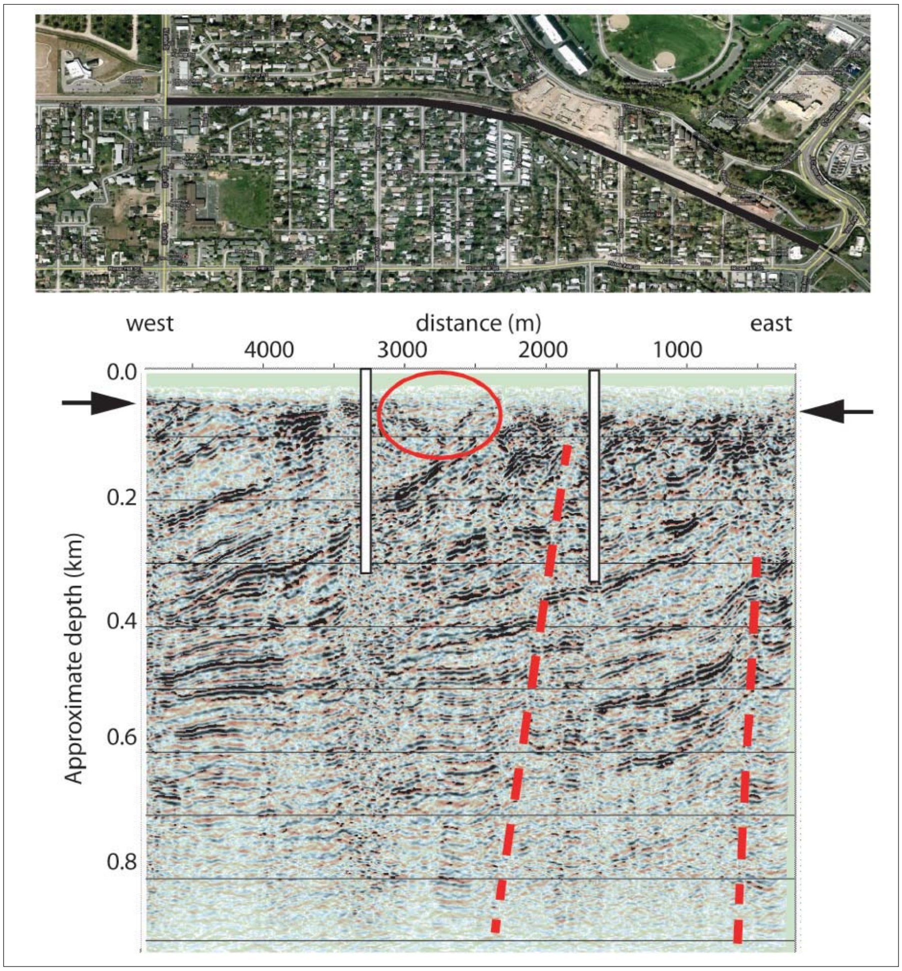

Figure 5. *(top) Aerial photo and seismic reflection profile location along a railroad and residential street in Boise, Idaho. (bottom) Seismic reflection image from a groundwater study in Boise, Idaho where prograding delta sands and mudstones dominate the stratigraphy in the upper 1 km. Red dashed lines represent interpreted faults, the red circle represents a fluvial channel and groundwater target, and arrows represent the base of a shallow sand unit. Two deep wells act as control points for depth conversion and geologic interpretation.*

accelerated weight drop (Figure 1) using 3-m geophone and source spacing. Traffic proceeded along the residential road while four individual shot records were recorded at 434 stations. The student crew placed geophones mostly in private property easements along the road shoulders. Power lines appeared overhead and many geophone stations were skipped due to road and driveway crossing. Processing steps included cultural noise attenuation as described above and diversity stack to remove traffic signal.

A lateral change in basin stratigraphy and a relatively flat basal reflector characterize this seismic image (Figure 4). Although I do not identify evidence for active normal faulting on the seismic profile, fluvial architecture and bedrock topography are mapped with the aid of nearby water wells and clear seismic character. The lack of reflectors in the upper 100 m of the northern portion of this profile suggests coarse-grained, laterally discontinuous alluvium dominates the basin while alternating coarse and fine-grained laterally continuous alluvial deposits are found along the southern portions of the profile. Rapid deployment using a small weight drop provided a clear image of subsurface stratigraphy with a center frequency of approximately 100 Hz. This acquisition approach has led to more seismic profiling at a greatly reduced cost compared to an equivalent vibroseis survey.

Boise, USA: aquifer characterization. Over the past decade, in collaboration with the state of Idaho, I have acquired a number of seismic reflection profiles throughout Boise, Idaho to map stratigraphy and geologic structures with the intent of improving the understanding of groundwater resources for the residents of southwest Idaho (Liberty et al., 2001). These profiles have been acquired in downtown areas and residential neighborhoods. Figure 5 shows an aerial map and seismic profile from an area in Boise where the groundwater resource in the upper 1 km was poorly understood due to complex basin stratigraphy, a low-permeability mudstone-dominated basin sequence, faulting, and shallow interbedded basalt flows (e.g., Wood, 1994).

I used a 120-channel seismograph with 5-m source and receiver station spacing to produce a 60-fold seismic reflection section (Figure 5). Portions of this profile were acquired along a railroad right-of-way, while other portions were acquired along residential streets. Vehicle traffic was encountered along the length of the profile and power lines were present along the length of the profile. The engineered fill of a railroad grade can reduce source and receiver coupling in places and can produce significant near-surface lateral velocity contrasts. However, these difficulties did not prevent high-quality seismic reflection data from being acquired along the length of the profile.

The alternating mudstones and sands of the Idaho Group prograding delta sequence overlie a shallow, yet extensive sand aquifer at 30–50 m depth along the length of the profile (Figure 5; Wood, 1994; Liberty et al., 2010). This sand aquifer is characterized by a seismically transparent zone overlying west-dipping strata. Additionally, a shallow sand channel cuts the central portion of the seismic profile (position 2750) and may provide a good source for shallow groundwater. Offset reflectors at depth suggest normal faults have shaped the evolution of the basin and may influence deep groundwater flow. Water wells, spaced more than 1 km apart that extend to

~300 m depth, show similar lithologies in each well. However, this seismic image suggests different stratigraphic units are encountered within each well due to depositional dips that approach 10°. Therefore, groundwater pumped from the two adjacent wells will draw from different aquifer units, and in some cases, these aquifers are separated by thick mudstone sequences that inhibit lateral groundwater flow. Seismic imaging in the Boise area has led to an increased understanding of the groundwater resource and the stratigraphy and structures of the Western Snake River Plain.

Summary

High-quality seismic reflection data can be obtained in urban areas using low-cost hammer sources along city streets and narrow urban corridors. Acquisition and processing strategies can significantly reduce much of the large-amplitude signal related to traffic and other sources of cultural noise. Strategies such as diversity stacking common source point data will balance high-amplitude coherent traffic signals relative to reflection returns, but require recording individual field shots. Processing steps that include match filters to subtract power-line signals help retain a broad-band reflection response while removing high-amplitude, narrow bandwidth cyclic signals that can overwhelm reflection amplitudes. Although off-time (evening or weekend) acquisition along culturally quiet transects is optimal, these opportunities may be unavailable or undesired in urban and suburban areas. Examples from earthquake hazards and groundwater studies show high-quality hammer seismic reflection results through urban corridors at a low cost. These inexpensive seismic sources, combined with acquisition and processing strategies described here, can lead to an increased understanding of many geologic and hydrogeologic targets at a variety of scales to benefit urban and project planners, reduce hazard risks, or quantify urban resources. TLE

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