10-2018

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Edward W. Woolery
University of Kentucky, ewoolery@uky.edu

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Digital Object Identifier (DOI)

https://doi.org/10.1016/j.eng.2018.08.009

Notes/Citation Information

Published in *Engineering*, v. 4, issue 5, p. 694-701.

Engineering 4 (2018) 694–701

Contents lists available at ScienceDirect

Engineering

journal homepage: www.elsevier.com/locate/eng

Research
Applied Geophysics—Article

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Edward W. Woolery

Department of Earth and Environmental Sciences, University of Kentucky, Lexington, KY 40506-0053, USA

A R T I C L E   I N F O

Article history:
Received 8 April 2017
Revised 31 March 2018
Accepted 27 August 2018
Available online 5 September 2018

Keywords:
Geophysics
Seismic reflection
Shear-wave
Near-surface
Dam safety

A B S T R A C T

Assessing subsurface characteristics and imaging geologic features (e.g., faults, cavities, low-velocity layers, etc.) are typical problems in near-surface geophysics. These questions often have adverse geotechnical engineering implications, and can be especially acute when associated with high-hazard structures such as large earthen flood-control dams. Dam-related issues are becoming more frequent in the United States, because a large part of this major infrastructure was designed and constructed in the early- to mid-twentieth century; these dams are thus passing into the latter stages of their design life, where minute flaws that were overlooked or thought to be insignificant in design/construction are now proving problematic. The high-hydraulic heads associated with these structures can quicken degradation of weak areas and compromise long-term integrity. Addressing dam-related problems solely with traditional invasive drilling techniques is often inadequate (i.e., lack of lateral resolution) and/or economically exorbitant at this scale. However, strategic geotechnical drilling integrated with the broad utility of near-surface geophysics, particularly the horizontally polarized shear-wave (SH-mode) seismic-reflection technique for imaging the internal structural detail and geological foundation conditions of earthfill embankment dams can cost-effectively improve the overall subsurface definition needed for remedial engineering. Demonstrative evidence for this supposition is provided in the form of SH-wave seismic-reflection imaging of *in situ* and engineered as-built components of flood-control embankment dams at two example sites in the central United States.

1. Introduction

Societal demands for flood control, water resources, and domestic/industrial energy helped initiate a prolific period of dam design and construction throughout the United States during the early- and mid-twentieth century [1]. During much of this time, engineering efficiency and economic practicality allowed civil projects, particularly earthfill embankment dams, to utilize suitable *in situ* earth materials (i.e., clay, sand, and gravel) for impervious cutoffs, filter drains, and other fundamental structural elements. It was not until the near-catastrophic dam failures associated with the 1971 San Fernando earthquake in southern California that more stringent consideration was given to the practice of using *in situ* materials as part of a dam's composition [1]. Subsequently, most regulatory agencies required the excavation and replacement of unlithified natural materials with engineered fill in all aspects of high-hazard dam design and construction. However, the *in situ* natural materials used in the earlier structures retained the potential for having undiscovered zones of adverse geotechnical properties (e.g., soft or low seismic-velocity zones, etc.), or acting to mask the presence of unfavorable geologic features (i.e., faults, karst, etc.) in the underlying bedrock foundation. Depending on the particular site conditions, resultant problems associated with these unknown geotechnical flaws may take decades to manifest.

Change orders or other post-design alterations often occur during the construction phase of any project, but can be especially numerous and significant for large complex structures such as flood-control dams [2]. Although modern digital tracking systems and databases provide a more complete engineering archive, it should not be surprising that many construction modification records made during the early period of prolific dam building have been lost or poorly documented due to the large number of amendments and record-keeping practices of the time. Nevertheless, these previous standards of practice can make assessing *in situ* geological or as-built engineered features within or beneath older earthen embankment dams a common source of geotechnical uncertainty.

E-mail address: woolery@uky.edu

https://doi.org/10.1016/j.eng.2018.08.009

All of these issues are of particular concern for large embankment dams and other high-hazard structures, because a large part of this infrastructure is passing into the latter stages of design life where minute flaws, which were overlooked or thought to be insignificant in the original design and/or construction phase, are proving problematic. Moreover, these geotechnical conditions can be especially consequential for structures exposed to high-hydraulic heads such as flood-control dams, where degradation can be accelerated and long-term integrity compromised.

Traditionally, solutions to geotechnical dam problems have largely relied on engineering measurements derived from various invasive drilling methods [1]; however, this approach can be ineffective (e.g., lack of lateral resolution) and/or cost exorbitant at this size and scale. In addition, the boreholes are generally distributed evenly across the project "footprint," thus problem areas can easily go undetected. However, a target-based drilling strategy can be technically and economically more effective by integrating the broad utility of noninvasive near-surface geophysics. Having said that, the selected geophysical method must be physically capable of resolving the geotechnical targets and objectives. The horizontally polarized shear-wave seismic-reflection technique can often provide the required resolution and optimal imaging for large embankment dams, including engineered structural features and *in situ* geological foundation conditions. This supposition was documented at two earthfill flood-control dams in the central United States. Notwithstanding the high-noise conditions at both dams, the SH-wave seismic-reflection method proved successful for imaging low-impedance intra-embankment boundaries separating *in situ* geologic sediment and compacted engineered borrow-fill of equivalent material (i.e., impervious cutoff), as well as buried as-built concrete elements (i.e., bulkhead cutoff and outlet works conduit). These results provide corroborative evidence for utilizing noninvasive cost-effective near-surface geophysics as a supplement to traditional drilling programs at large-scale civil works projects.

2. Background

SH-wave seismic-reflection profiles collected at two earthfill flood-control dams in the central United States were used in order to evaluate their geophysical effectiveness for imaging and locating the following: ① low-impedance intra-embankment boundaries separating engineered fill and *in situ* geologic materials incorporated into the dam design as impermeable cutoffs and drain filters; and ② relatively small, fundamental elements required for a properly functioning dam (i.e., interior concrete outlet conduit), as well as features added during the construction phase for the abatement of a foundation hazard discovered during excavation at the dam abutment (i.e., concrete bulkhead cutoff).

Dam Site 1, located in northern Indiana, was constructed during the early to mid-1960s (Fig. 1(a)). It is a compacted earthfill embankment approximately 2.4 km in length with a maximum height of nearly 53 m above bedrock. The embankment is founded on approximately 25 m of glacio-alluvial sediment overlying a Silurian limestone bedrock. The 788 m long SH-wave seismic-reflection profile was acquired along the downstream edge of the dam's crest, approximately 12 m downstream of the axial center line. It originated at the right abutment and terminated at the onset of the centrally located outlet works. An earlier interpretation of these seismic-reflection data assessed existing geologic hazards associated with mature karst development in the limestone foundation beneath the embankment, which were encountered during both design and construction [3]. The previous study successfully applied high-resolution SH-wave seismic-reflection surveying of the bedrock surface beneath the dam in order to approximate the depth to bedrock, and to identify signal anomalies indicative of unfavorable geological foundation conditions (i.e., karst). The data are used here to evaluate the SH-wave seismic-reflection method for imaging intra-embankment boundaries separating engineered fill (compacted glacial till borrow) and *in situ* glacial till and alluvial sand used for an impermeable cutoff and horizontal drain filter, respectively. The data were also used in order to assess the geophysical ability to resolve the internal basal concrete conduit associated with the dam's outlet works.

Dam Site 2, located in southern Kentucky, was constructed during the mid- and late 1960s, and consists of a rock-fill dam, earthen dike, gate-controlled outlet works, and an open-cut spillway between the dike and dam. The dike is the structure of interest for this study (Fig. 1(b)). It is an appurtenant impoundment dam 595 m in length and approximately 31 m in height, founded directly on Mississippian limestone. The SH-wave seismic-reflection transect was collected orthogonal to the centerline and atop the near-vertical zonated backfill in an excavated notch just above the base of the right dike abutment (Fig. 1(b)). These data were used to evaluate the effectiveness for geophysically imaging a concrete bulkhead cutoff, the excavated notch rock surface, and the engineered material zonation used in the backfill.

3. Methods

Pioneering research associated with near-surface high-resolution seismic-reflection imaging primarily incorporated primary wave (P-wave), or compressional wave, energy, because of the higher frequency characteristics and operational control

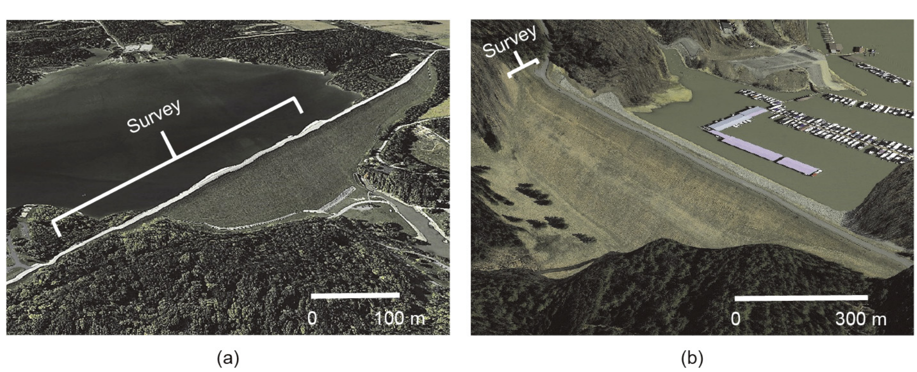

Fig. 1. Two earthfill embankment dams in the central United States were imaged with SH-wave seismic-reflection techniques to evaluate this method's ability to distinguish small, high-impedance engineered features (i.e., concrete conduits and bulkheads), as well as larger, low-impedance boundaries such as those separating *in situ* geologic sediment and compacted engineered backfill that uses equivalent local borrow material. (a) Dam Site 1 and (b) Dam Site 2 are located in northern Indiana and southern Kentucky, respectively. (Source: Google Earth, 2016)

offered by the various weight-drop, projectile, and vibratory sources (e.g., Refs. [4–8]). However, a groundwater masking effect can be problematic for P-wave energy that is used to image the solid matrix in subsurface environments where relatively low-velocity geologic media and their elastic impedance are water-saturated, such as the unlithified sediment generally found in the near surface of active fluvial and alluvial environments. The horizontally polarized shear-wave (SH-mode) common-midpoint (CMP) method has subsequently proven an amenable alternative for imaging these low-velocity, water-saturated, near-surface conditions ($\ll$100 m) (e.g., Refs. [2,9–18]). Shear waves can be more responsive for near-surface imaging because they are "framework waves" (i.e., not subjected to groundwater masking), and thus propagate with the solid media relative to the fluid-sensitive P-wave. The SH phase is theoretically easier to identify, unlike vertically-polarized shear-wave (SV-mode) signals, because of the lack of mode conversion at ideal impedance boundaries [19]. Relative to P-wave energy, the lower velocity SH-wave has an optimal spatial window at the nearer offset; it also expands the temporal separation between the reflecting boundaries [20]. An increased temporal window permits more distinct, accurate identification of the reflecting boundaries that result from the larger separation between the signal and coherent noise events, while the nearer offset optimal recording window decreases the potential for introducing adverse wide-angle-reflection effects. More importantly, however, experience shows that although SH-waves commonly have frequency content only one-half to one-third that of P-waves, the velocities of P-waves are 5 to 10 times higher than those of SH-waves; therefore, resolution commonly improves by a factor of two to three when using SH-waves [14,20]. This is a very important point when considering relatively small subsurface targets. For example, the major reflection horizons observed for the data presented herein have an average velocity range of 220–400 $m{\cdot}s^{-1}$, and a dominant frequency of approximately 50 Hz. This yields a temporal resolvable limit (i.e., calculated by the one-quarter wavelength criteria [19]) ranging between 1.1 and 2.0 m. The detectable limits are considerably smaller (i.e., $\lambda/8$–$\lambda/20$). The spatial resolution of the reflecting horizons is constrained between approximately two and four shot points, based on the radius of the first Fresnel zone [19].

In addition to overall varying targets and objectives requiring varying acquisition parameters, the seismic data collection at the two dam sites occurred several years apart; as a result, there was a deployment of different recording systems. The Site 1 survey used a Geometrics StrataView® 48-channel engineering seismograph and two inline spreads of 24 and 30 Hz, with horizontally polarized Mark Products® geophones with 7.5 cm ground spikes. The seismograph was a 24-bit system with an instantaneous dynamic range of 115 dB. The sampling interval was 0.5 ms, and a 25 Hz low-cut acquisition filter and a 250 Hz high-cut anti-alias filter were used. Due to several nearby electrical power sources, a 60 Hz notch filter suppressed potential unshielded noise. The shear-wave energy source was a modified section of steel H-pile ($\sim$11 kg) struck horizontally with a 4.5 kg sledge hammer. The hold-down weight of the H-pile was between approximately 70 and 80 kg, including the weight of the hammer swinger and the H-pile section. The H-pile flanges and hammer swings were perpendicular to the geophone spread for SH-mode generation. The flanges were in prepared slit trenches in order to resist movement and maximize the energy couple with the ground. The geophones in the two inline spreads were spaced at 2 m intervals, for a total spread length of 96 m. The production survey maintained a 2 m near offset between the end-on shot point and the first active geophone. Example processing steps for the pre-stack field gathers are given in Fig. 2. These seismograms consist of two sets of three consecutive data field files collected near the first and last parts of the survey. The primary reflection events had a two-way travel time (TWTT) of 70–300 ms.

The Site 2 SH-wave seismic-reflection data were collected with two 24-channel Geometrics Geode® seismographs, and with a geophone array similar to that used in Site 1 but with 1 m spacing. The instrumental fidelity was equivalent to the seismograph used at Site 1, but was controlled with a separate laptop computer. Data sampling at Site 2 occurred at 0.25 ms intervals. The digital acquisition filters included 15 Hz low-cut and 60 Hz notch filters. The shear-wave energy source was similar to that used in Site 1, but involved a smaller H-pile (3 kg) and hammer (0.9 kg). Fig. 3 shows processing steps for the example pre-stack field gathers at Site 2. These are three single gathers that were selected from near the beginning, middle, and end of the survey.

Each SH-wave survey used instrumental polarity reversals and correlative reverse hammer impacts on both sides of the energy source for each shot point. This ensured correct identification of the SH-wave energy and decimated P-wave contamination. In addition, hammer blows were stacked (or linearly superimposed) between four and six times per shot point. Both sites realized minimal acquisition downtime; however, work was suspended during prolonged wind gusts and/or passing traffic.

Data acquisition parameters for the two sites are in Table 1. Although it is generally preferable not to apply acquisition filters, the local conditions provided justification for the partial use at the two sites. The processing for both data sets was on a personal computer using the commercially available VISTA seismic data processing software, versions 7.0 and 13.0, along with a conventional shallow CMP processing sequence. The primary signal processing steps focused on coherent noise muting, digital filtering, trace editing, appropriate trace balancing, and careful correlation statics for improving the pre-stack quality of the events seen on the raw field file. This is a minimal, but acceptable, approach for processing shallow seismic-reflection profiles [21,22]. These standard near-surface data-processing procedures are similar to those used in the petroleum industry, but appropriately scaled

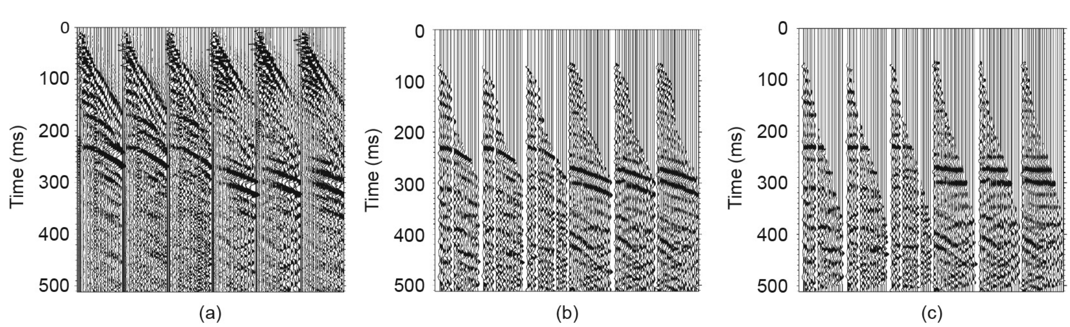

Fig. 2. Example Dam Site 1 field files: two sets of three consecutive data field files collected near the first and last parts of the survey. (a) Raw/spherical-gain corrected data; (b) trace-killed/muted/filtered data; (c) normal moveout corrected data.

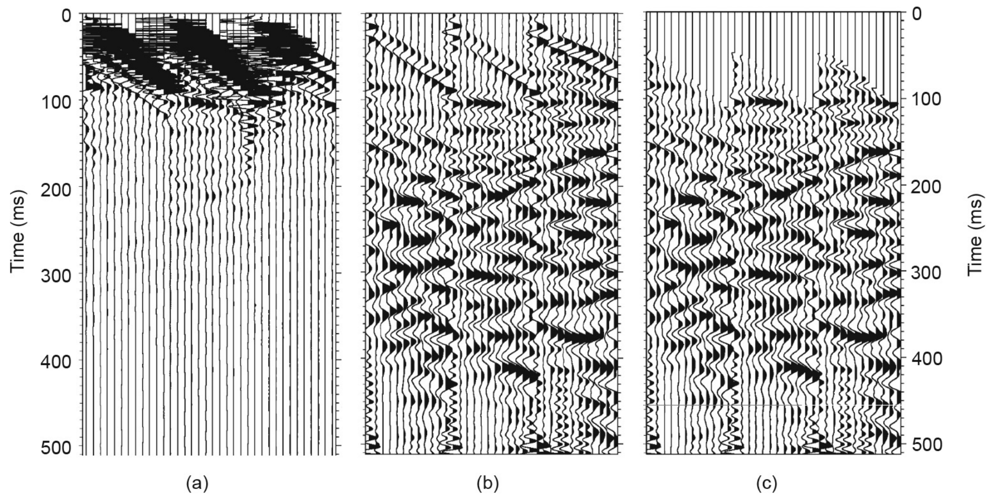

Fig. 3. Example Dam Site 2 field files: three data files collected near the beginning, middle, and end of the survey. (a) Raw data; (b) filtered/balanced data; (c) top-mute corrected data. Note the normal (image (a)) and reverse (image (c)) moveout ringing below 200 ms TWTT in the gathers; this is probably offline noise associated with the excavated notch and/or the dike's upstream and downstream free face.

Table 1
Acquisition parameters and general signal processing procedures for the CMP seismic-reflection surveys at Sites 1 and 2.

Field parameters	Site 1	Site 2
Source	4.5 kg hammer with 11 kg H-pile	0.9 kg hammer with 3 kg H-pile
Acquisition low-cut	25 Hz	15 Hz
Acquisition high-cut	250 Hz	Out
Geophone	30 Hz	30 Hz
Near offset	2 m	1 m
Group/shot interval	2 m	1 m
Sample interval	0.5 ms	0.25 ms
Fold	12	6
Vertical stack	4	4

and conservatively applied. No other shallow-reflection processing (i.e., deconvolution, migration, etc.) were applied because of the insignificant signal quality improvement.

4. Results

4.1. Dam Site 1

The 12-fold, 788 m long, east–west SH-wave seismic-reflection image was parallel with the dam's centerline and along the downstream edge of the embankment crest (Fig. 4). The profile provides subsurface coverage across the right half of the dam (i.e., between the right abutment and outlet works). The uninterpreted and interpreted images, along with a borehole-derived geologic profile for correlative assistance, are provided in Fig. 5. Trace numbers along the top of the reflection profiles are at 100 m intervals. In general, the data quality is good along the entire length of the profile. This was somewhat surprising, because significant noise was associated with the reservoir water discharge from the downstream outlet works. The relatively high-frequency shear-wave geophones may have acted as a pre-emphasis filter, minimizing the record contamination. The continuous, relatively coherent, large-amplitude reflection (doublet) visible between 150 and 300 ms TWTT (i.e., ~24 and 53 m depth) across the profile is the top-of-bedrock unconformity [3]. This reflection event provides a clear image of the terraces and former river channel. The previous interpretation for the abrupt loss of coherency at two locations in the "bright" bedrock reflector (Fig. 5) was karst solutioned joints and/or cavity collapse [3]. The associated seismic-derived depths to bedrock were within 5% of those expressed in the geologic profile. A borehole targeted the karst interpretation at approximately trace number 410, and found 6.5 m lower-than-expected top-of-rock elevation from the geologic profile [3]. The borehole observations found a 6.5 m interval below the expected top-of-rock consisting of very soft foundation material (i.e., *N*-values < 5), a primary indicator of karstic cavity fill likely formed from embankment "piping." In addition, during excavation operations for the final remedial positive cut-off wall constructed through the limestone foundation and keyed into a lower shale unit, mature karst solution features were found in both anomalous areas identified in the initial interpretation.[†]

Numerous intra-embankment reflectors are also apparent; these horizons agree reasonably well with the areas and elevations of engineered fill and *in situ* foundation soils described in the borehole-derived profile (Fig. 5). Of particular note is the steeply dipping reflector observed between traces 225 and 600, which is visible between TWTTs 70 and 150 ms. This event correlates with the boundary separating the engineered fill and glacial till interpreted in the borehole-derived geologic profile. The "onlap" characteristic of the shallow intra-embankment reflection just above the *in situ* till boundary near trace 250 (and ~100 ms TWTT) is interpreted as emplaced engineered backfill abutted with the *in situ* till (Fig. 5). Although the borehole logs mention weathering being observed in the shallow till, the final geologic profile for the design document does not explicitly interpret a weathered zone for the till. A slightly steeper dipping reflector just beneath the interface is interpreted here as the base of the weathered zone. This zone may indicate a colluvial wedge. Other discontinuous reflectors appear within the till, and may represent the scattered sand and gravel bodies described in the geologic profile; however, this is speculative, and additional corroboration is required to verify these interpretations. The interpreted package of reflectors within the old river channel is the *in situ* alluvium that was left to act as a horizontal drain. The far-west side of the channel has a steeply rising reflector, and correlates with the onset of the outlet works in the as-built reports. A relatively strong shallow reflector is present between ~80 and 90 ms TWTT, but appears to be discontinuous, likely due to the top muting. This horizon may correlate with the top of the vertical "chimney" drain constructed on the downstream

† Kenneth Henn, United States Army Corps of Engineers, 2010, personal communications.

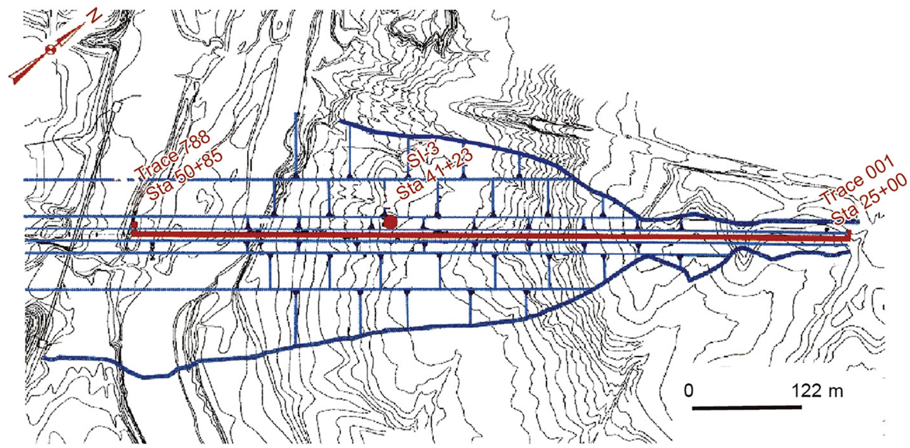

Fig. 4. Footprint of the Dam Site 1 embankment overlying original topography (modified from Ref. [3]). The northeast–southwest-oriented heavy line, between station labels 25+00 and 50+85, indicates the location of the reflection profile along the crest, just downstream of the centerline. The beginning and ending traces are also shown, along with their corresponding stationing. SI-3 is the instrumentation well that was used for the Woolery [3] downhole seismic test. Note the old river channel crossing beneath the southwest end of the profile. Also note that the outlet conduit was located at the southwest edge of the old channel. Sta: station.

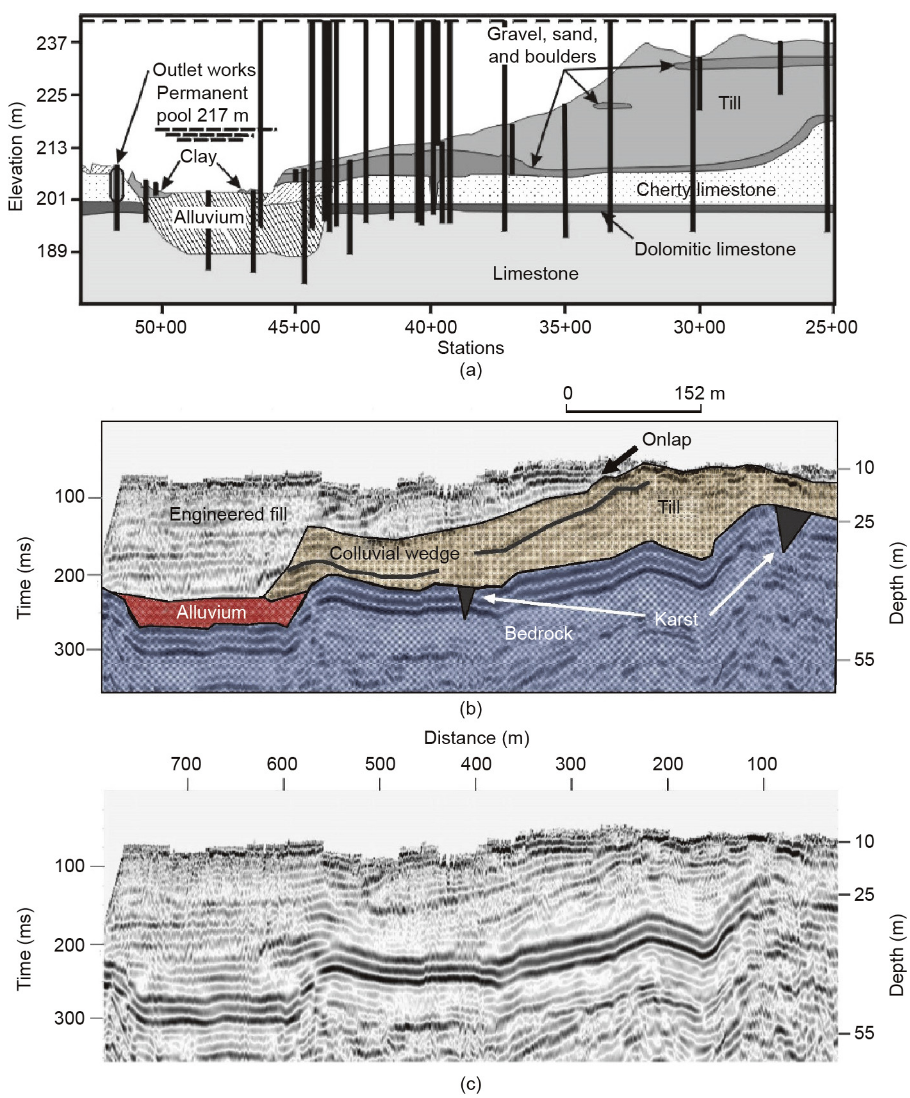

Fig. 5. (a) Geologic profile constructed from design and post-construction phase borehole information; (b) the interpreted SH-wave seismic-reflection image; (c) the uninterpreted image. (Modified from Ref. [3])

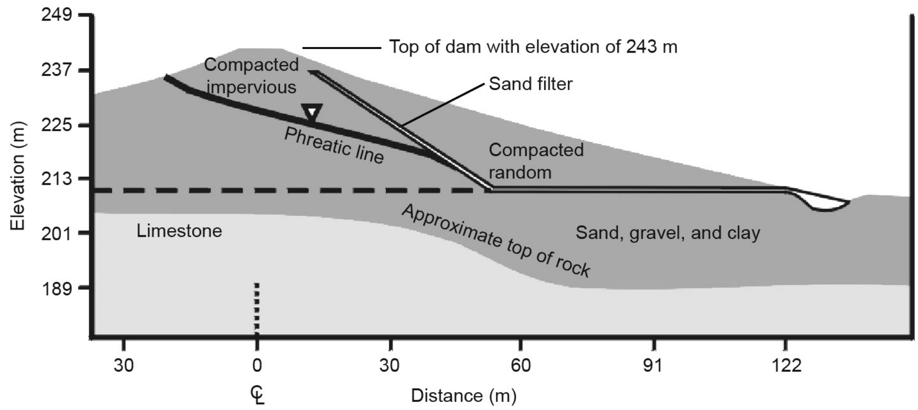

Fig. 6. Cross-sectional view of the embankment at approximately Station 41+00 (Fig. 5). This shows the approximate location of the phreatic surface and its intersection with the vertical "chimney" drain. Discharge of controlled seepage is through relief wells along the downstream "toe" of the dam.

side of the crest (Fig. 6). A reduced aperture for the acquisition array would be necessary to better image this feature (i.e., contract the shallow muted zone) and corroborate the interpretation. Nevertheless, the overall interpretive evidence suggests that the original as-built geologic profile for the project was well constrained, and is a reliable source of geotechnical detail for most subsequent remedial design actions.

4.2. Dam Site 2

Acquisition of the six-fold, 37 m long, SH-wave seismic-reflection subsurface image was orthogonal to centerline, approximately 10 m inside the Site 2 dike's right abutment. The ground-surface elevation is approximately 229 m above mean sea level (AMSL), and the first subsurface image point was located 14 m upstream of the dike centerline, with the terminal point 23 m downstream of the centerline (Fig. 7). This location is the as-built location that was given in the change order for a concrete bulkhead to act as a positive cutoff for potential seepage through a large karst conduit discovered in the right abutment (Fig. 7). The location is set back approximately 15 m into the excavated notch from the originally planned location. The top-of-rock profile, determined from design through post-construction drilling programs, shows the irregular nature of this horizon (Fig. 7). Also shown is the original planned location for the bulkhead cutoff. Note the highly irregular or "pinnacled" top of limestone that is typical of a mature karstic environment. More importantly, the large subhorizontal solution conduit, which was discovered during design drilling investigations and confirmed during construction excavation, had the potential to provide an uncontrolled seepage path of reservoir water through the impoundment structure. The emplaced bulkhead acted as a positive cutoff; however, the as-built location was set back further into the abutment notch because of the highly weathered poor rock quality found at the original planned location. Fig. 8 is a simplified design schematic for the zoned engineered backfill in the excavated abutment notch. The elevation for the base of the notch, top of bulkhead, and abutment ground surface (at the survey location) is 214, 217, and 229 m AMSL, respectively. The final uninterpreted and interpreted Site 2 reflection profile is provided in Fig. 9. The profile consists of 74 seismic traces spaced 0.5 m apart. The notch clearly exhibits a synformal reflection event between seismic traces 7 and 61, and between 65 and 135 ms TWTT. The six horizontal relatively large-amplitude reflection wavelets visible between seismic traces 25 and 35, and at 135 ms TWTT, is the notch base. Using a shear-wave velocity of 220 m·s^{-1}, this places the base of the notch approximately 15 m below ground surface, verifying the as-built elevation (i.e., 214 m AMSL). The bedrock surface outside the notch appears to be undulating but relatively coherent. A prominent "bright" reflection (i.e., higher relative frequency and larger amplitude) manifests within the engineered backfill material and notch interior. This is evident between seismic traces 28 and 33, and at 100 ms TWTT. This reflection is from the top of the concrete bulkhead cutoff. The 220 m·s^{-1} shear-wave velocity yields a depth of 11 m for this reflector, which is approximately equivalent to the as-built recorded elevation (i.e., 217 m AMSL). The ability to noninvasively verify the recorded as-built location without advancing one or more invasive boreholes minimized the potential for compromising the bulkhead's cutoff integrity. However, it is also notable that there are no observable signal variations distinguishing between the clay core, sand filter, and rock shell. Truncation of the seismogram was below 200 ms TWTT, because of no target interest and multiple contamination (i.e. "ringing") that was likely associated with the fill/rock interface.

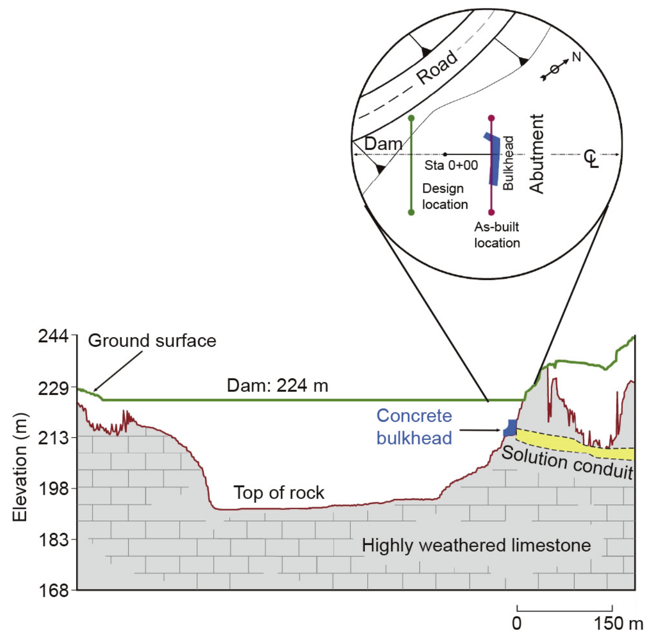

Fig. 7. The inset (top) is a map view of the design and as-built locations for the concrete bulkhead. The green line is the original planned location for the bulkhead, and the red line shows the setback location and SH-wave seismic-reflection profile. The top-of-rock profile (bottom) shows the highly varying rock surface, indicative of a mature karstic environment. The original planned location for the concrete bulkhead is where the solution conduit intersects the rock-embankment boundary. The bulkhead was set back to more favorable rock conditions during construction.

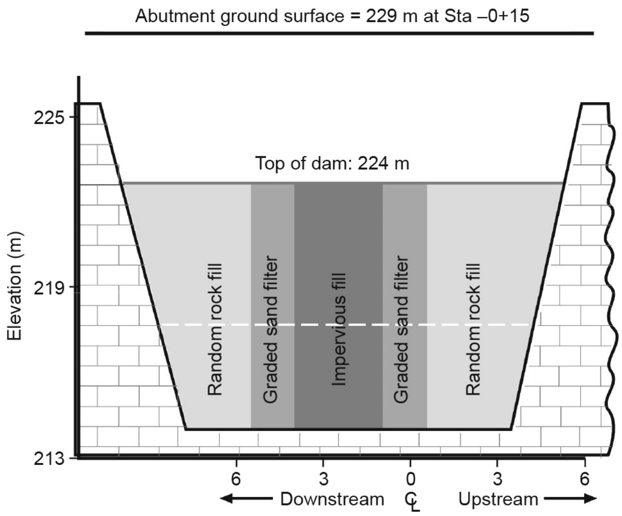

Fig. 8. Idealized design cross-section of the notch and zoned backfill. The white dashed line is the as-built top of the cutoff, at 217 m AMSL. The bottom of the notch is at 214 m AMSL. The SH-wave seismic-reflection profile was over the as-built location, at Station −0+15. Ground elevation is approximately 229 m AMSL.

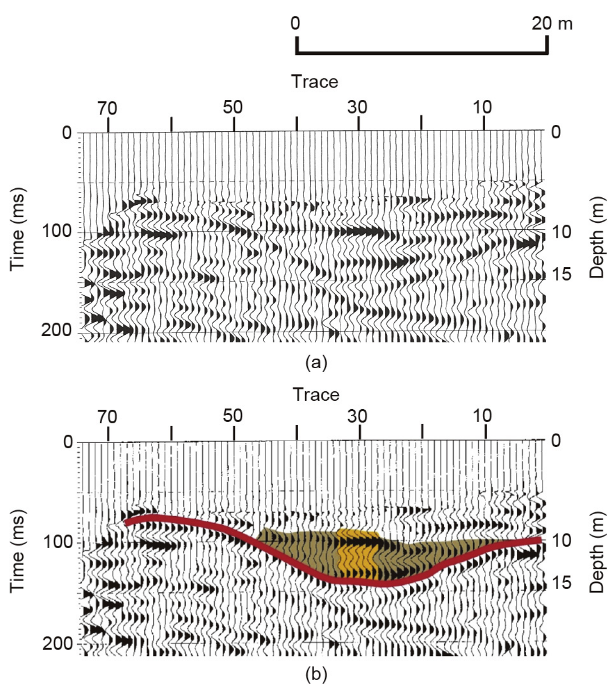

Fig. 9. The (a) uninterpreted and (b) interpreted SH-wave seismic-reflection profile across the backfilled notch on the dike's right abutment. Trace numbers refer to the subsurface sample points, and trace separation is 0.5 m. The red line is the interpreted notch and the orange zone marked by the high amplitude reflectors at 100 ms TWTT is the top of the concrete bulkhead. The calculated elevations for the base of the notch and the top of the bulkhead correlated well with the as-built descriptions.

5. Conclusions

Solving geotechnical problems with traditional geotechnical exploration (i.e., drilling) can be inefficient and often inadequate at high-hazard earthfill embankment dams [16]; however, near-surface geophysical exploration using the SH-mode seismic-reflection method to supplement invasive drilling has improved the geotechnical assessment of two earthen flood-control dams in the central United States. The cost-effective, noninvasive, SH-wave seismic-reflection surveys clearly identified the bedrock foundation at both dam sites, as well as many primary intra-structural features. Prior to performing the survey at Site 1, it was uncertain whether the seismic-reflection method could physically resolve the contact separating the engineered fill and the *in situ* geological sediment (i.e. glacial till) used for part of the impermeable cutoff, because the fill consisted of a compacted local "borrow" of the equivalent glacial till. However, the seismic-reflection survey showed that sufficient impedance does exist between the *in situ* glacial till and the compacted fill to provide a coherent reflected signal. A more subtle impedance boundary was also observed beneath the fill-till boundary. This reflection was a weathering boundary or colluvial wedge in the *in situ* glacial till. The *in situ* alluvium in the former river channel also provided measurable elastic contrast. At Site 2, an image of the notch excavation in the abutment bedrock was clear; however, discriminating the vertical zonation for the engineered fill in the excavated notch was unsuccessful. In addition, the resolution of the SH-wave seismic-reflection signal permitted the imaging of relatively smaller engineered features, including a concrete bulkhead cutoff at Site 2 and part of the outlet works conduit at Site 1. These results corroborate the supposition that high-resolution SH-mode reflection surveys are a viable tool for evaluating dam safety issues, as well as other geotechnical problems in earthfill embankment dams.

References

[1] Federal Emergency Management Agency. Federal guidelines for dam safety risk management Report. New York: Federal Emergency Management Agency; 2015.

[2] Nunnally SW. Construction methods and management. 8th ed. Upper Saddle River: Prentice Hall; 2011.

[3] Woolery EW. SH-wave reflection images of anomalous foundation conditions at the Mississinewa dam, Indiana. J Environ Eng Geophys 2002;7(4):161–8.

[4] Steeples DW, Knapp RW. Reflections from 25 feet or less [expanded abstract]. In: The 52nd Annual International Meeting and Exposition, Society of Exploration Geophysicists; 1982 Oct 17–21; Dallas, TX, USA; 1982. p. 469–71.

[5] Hunter JA, Pullan SE, Burns RA, Gagne RM, Good RL. Shallow seismic reflection mapping of the overburden-bedrock interface with the engineering seismograph—some simple techniques. Geophysics 1984;49(8):1381–5.

[6] Pullan SE, Hunter JA. Seismic model studies of the overburden-bedrock reflection. Geophysics 1985;50(11):1684–8.

[7] Knapp RW, Steeples DW. High-resolution common depth point seismic reflection profiling, instrumentation. Geophysics 1986;51(2):276–82.

[8] Knapp RW, Steeples DW. High-resolution common depth point seismic reflection profiling, field acquisition parameter design. Geophysics 1986;51(2):283–94.

[9] Goforth T, Hayward C. Seismic reflection investigations of a bedrock surface buried under alluvium. Geophysics 1992;57(9):1217–27.

[10] Woolery EW, Street RL, Wang Z, Harris JB. Near-surface deformation in the New Madrid seismic zone as imaged by high resolution SH-wave seismic methods. Geophys Res Lett 1993;20(15):1615–8.

[11] Woolery EW, Wang Z, Street RL, Harris JB. AP- and SH-wave seismic reflection investigation of the Kentucky Bend scarp in the New Madrid seismic zone. Seismol Res Lett 1996;66(2):67–74.

[12] Woolery EW, Street RL, Harris JB, Wang Z, McIntyre J. Neotectonic structure in the central New Madrid seismic zone: evidence from multi-mode seismic-reflection data. Seismol Res Lett 1999;70(5):554–76.

[13] Woolery EW, Baldwin J, Kelson K, Hampson S, Givler R, Sundermann S. Site-specific fault assessment in the fluorspar area fault complex western Kentucky. Seismol Res Lett 2009;80(6):1035–44.

[14] Harris JB. Shear-wave splitting in Quaternary sediments: neotectonic implications in the central New Madrid seismic zone. Geophysics 1996;61(6):1871–82.

[15] Deidda GP, Balia R. An ultrashallow SH-wave seismic reflection experiment on a subsurface ground model. Geophysics 2001;66(4):1097–104.

[16] Woolery E, Street R. Quaternary fault reactivation in the fluorspar area fault complex of western Kentucky: evidence from shallow SH-wave reflection profiles. Seismol Res Lett 2002;73(5):628–39.

[17] Benjumea B, Hunter JA, Aylsworth JM, Pullan SE. Application of high-resolution seismic techniques in the evaluation of earthquake site response, Ottawa Valley, Canada. Tectonophy 2003;368(1–4):193–209.

[18] Pugin AJM, Pullan SE, Hunter JA, Oldenborger GA. Hydrogeological prospecting using P- and S-wave landstreamer seismic reflection methods. Near Surf Geophys 2009;7:315–27.
[19] Sheriff RE, Geldart LP. Exploration seismology [dissertation]. New York: Cambridge University; 1995.
[20] Woolery EW, Almayahi A. Shear-wave birefringence measurements in faulted near-surface sediment. Bull Seismol Soc Am 2014;104(3):1540–9.
[21] Steeples DW, Miller RD. Seismic-reflection methods applied to engineering, environmental, and ground-water problems. In: Proceedings of the 1st Symposium on the Application of Geophysics to Engineering and Environmental Problems; 1988; Denver, CO, USA. Denver: Environment and Engineering Geophysical Society; 1988.
[22] Baker GS, Young R, editors. Processing near-surface seismic-reflection data: a primer. Tulsa: Society of Exploration Geophysicists; 1999.