NATIONAL CAVE AND KARST RESEARCH INSTITUTE
SYMPOSIUM 8

PROCEEDINGS OF THE 16th MULTIDISCIPLINARY CONFERENCE ON

SINKHOLES AND THE ENGINEERING AND ENVIRONMENTAL IMPACTS OF KARST

First Edition

EDITORS:
Lewis Land
National Cave and Karst Research Institute
Carlsbad, New Mexico, USA

Clint Kromhout
Florida Geological Survey
Tallahassee, Florida, USA

Michael J. Byle
Tetra Tech, Inc.
Langhorne, Pennsylvania, USA

Organized by:

National Cave and Karst
Research Institute

CROSSHOLE MAPPING OF A SUBSURFACE VOID

Peter J. Hutchinson
THG Geophysics, Ltd., 4280 Old Wm. Penn Hwy., Murrysville, Pennsylvania, 15668 USA, pjh@thggeophysics.com

Maggie H. Tsai
THG Geophysics, Ltd., 4280 Old Wm. Penn Hwy., Murrysville, Pennsylvania, 15668 USA, mhb@thggeophysics.com

Abstract

Kentucky River Lock and Dam 8, Jessamine and Garrard Counties, Kentucky, were constructed in 1900 and have for the past 120 years experienced significant degradation due to karst geology. The cement capped wood-cribbed dam is anchored to the karstic Grier Limestone. Due to the dissolution of limestone, water seepage around and under the dam has created unstable conditions for the dam that required engineering rehabilitation many times over the years. A recent rehabilitation project to prevent river water from seeping under the dam included installing engineered secant grout curtains anchored into the Grier Limestone.

During the intrusive investigation a void was encountered in a boring in Cell 2. A secant grout curtain was proposed to prevent groundwater from migrating through the void. Six crosshole tomographic profiles between 4 cased borings imaged a fracture zone. The fracture zone displayed lower *p*-wave velocities in contrast to the surrounding material within the survey area. This low velocity zone is interpreted to be water- or mud-filled voids or vuggy zones within the fracture in the limestone.

Introduction

Kentucky River Lock and Dam 8 are located between Garrard and Jessamine Counties, Kentucky (Figure 1). Dam 8 has experienced deformation, erosion and collapse since its completion in 1900 primarily due to karst conditions (Welshans et al., 2011). The 120-year-old crib-work dam was repaired several times over the years and was, as of 2011, a concrete-capped, rock-filled timber crib dam (Figures 2 and 3). The original lock and dam were constructed between 1898 and 1900 as a timber crib structure, consisting of an outside frame of timbers filled with dirt and rock. A cement cap was installed in the 1920s. Construction from 1993–1995 included removing a river guide wall, filling downstream face voids with concrete, and placing derrick stone below the dam. In 2001 a concrete cutoff wall was built in the lock chamber and lock filling valves were sealed. Grout bags were placed along the far abutment in 2002 to cut off leakage. The replacement dam will be a concrete-filled cellular sheet pile structure upstream of the existing dam (USACE, 1999).

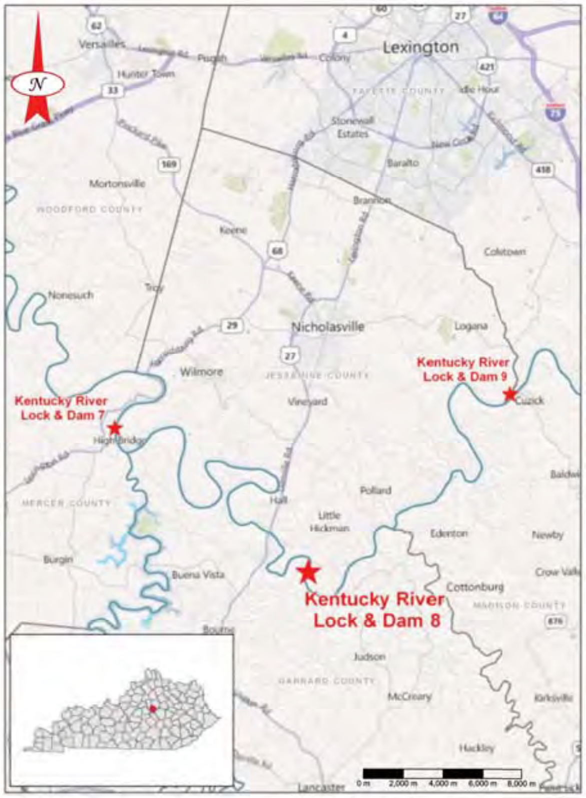

Figure 1. A location map of Lock and Dam 8 located south of Lexington, Kentucky.

Initial work included digging a series of borings to assess subsurface conditions prior to building coffer dams (Figures 4 and 5). Secant grout walls are to be installed to prevent groundwater from migrating under the dam. The replacement dam will be a series of concrete-filled cellular sheet pile structures installed upstream of the existing dam.

Boring B-13, within coffer dam Cell C-2, penetrated a 0.43 m void (Figures 3 and 6). The concern was that

Figure 2. *Aerial view to the northeast (upstream) of Dam 8 on the Kentucky River as of 2017 showing the completed concrete-filled cellular sheet pile structure.*

pumping the grout slurry into a boring with a void would cause the slurry to dissipate into the surrounding fractured rock and voids. This would prevent the secant curtain from restricting groundwater flow through or under the dam, potentially destabilizing the dam.

Geology

The dam site and surrounding area consist of the Middle Ordovician-aged Grier Limestone Member of the Lexington Group (Figure 7). The approximately 40-m thick Grier is a fossiliferous medium gray limestone with shale partings throughout its vertical extent (Walcott, 1970). The Grier resides conformable but gradationally to the overlying approximately 10-m thick Tanglewood Limestone Member and conformably overlies the 6-m thick Curdsville Limestone Member. Rock units in the vicinity of the dam are flat lying with little measurable dip (Hatton, 2018).

This dam site is located 2,400 m east of the Kentucky River Fault system. The Kentucky River Fault System is the north-bounding fault system of the Rome Trough, a Paleozoic-aged aulacogen (Vanarsdale, 1986). This fault was active after the deposition of the Lexington Group, and was possibly active up to 1 million years ago.

The Kentucky River Fault System has been described as having transpressive motion (compressional to strike-slip motion) that has not been overprinted by the multiple episodes of the Appalachian Orogenesis (Morisen, 2004). Transpressional movement probably occurred during the Pennsylvanian-Permian Allegheny Orogeny; however, this region probably evolved through polyphase faulting under separate yet distinct stress regimes from the Ordovician through the Quaternary.

Crosshole Tomography

Crosshole tomographic imaging is commonly used when high resolution deep seismic data is needed or a surface seismic survey cannot be performed. To collect a profile of *p*-wave velocity, the survey uses 2 cased borings; one serving as the source hole and the other as the receiver hole. A fixed array of geophones or hydrophones is placed in the receiver borehole, while a seismic wave is initiated from the source borehole. The seismic event is triggered at intervals over the length of the casing that covers the area of interest (Figure 8). Since the raypath

Figure 3. *Left photo shows the collapsed portion of the dam near the left abutment in 1994. Right photo shows dye leakage at the left abutment in 2001 (Welshans et al., 2011).*

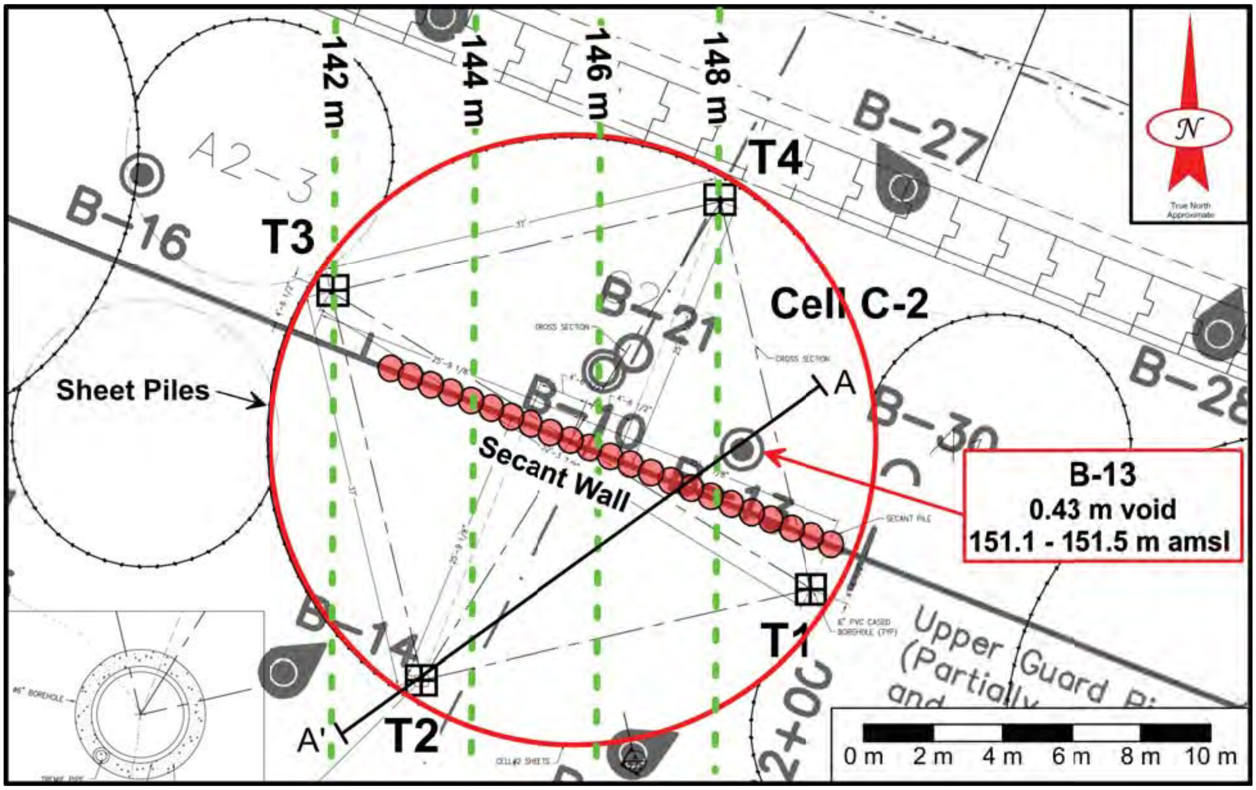

Figure 4. *Location of 4 crosshole borings (T-1, T-2, T-3, and T-4) and boring B-13 within coffer dam Cell C-2 from design drawing for the rehabilitation of the dam (Welshans et al., 2011). Depth contours (in m amsl) of a fracture zone are shown as green dashed lines.*

lengths between the borings are known, the 1-way travel-time of first arrival time of the seismic wave front can be used to calculate the velocity (V) of each raypath:

$$V=L/T$$

Where ***L*** is distance and ***T*** is time of first arrival of the wave front.

The exact distance between boreholes must be measured for each geophone and source to calculate the velocity from the arrival time of the first wave front. The position of each receiver and shot point within their respective boreholes were measured through a downhole deviation tool (Mt. Sopris; QL40-DEV). The deviation tool orientation sensor contains a 3-axis fluxgate magnetometer and a 3-axis accelerometer to accurately determine the inclination (tilt) and azimuth of the borehole (Figure 9). The vertical deviation of a borehole was used calculate the distance between boreholes.

Data resolution is determined by the number of shot locations that are acquired and distance between borings. The higher number of shot locations, the higher the data resolution because more raypaths overlap and their velocities are averaged (Figure 8). In processing, the raypaths are divided into a number of blocks where each block is assigned a velocity based on 1-way travel-time of overlapping traces. Velocities of each block are then calculated to produce an apparent velocity model. The model is compared to the actual measurements for consistency. Anomalous zones are detected by strong velocity contrasts within the data sets (Reynolds, 1997).

Crosshole Survey

Six cross-sections were collected between the 4 PVC (100 cm) grouted borings. A string of eight 1-m spaced 10 Hz hydrophones (Geospace MP-25-250 Sidewinder) were placed in water-filled receiver borings T1, T2, and T3. The bottom hydrophone was positioned at 142 m above mean sea level (amsl) in the borings and repositioned at 149 m amsl for full coverage over the 10-m vertical limestone rock interval of interest (Figure 8). The survey was modified from the initial 10-m interval and expanded to 14-m interval to collect more data above the elevation of the B-13 void.

Data were acquired to cover between elevations 142 and 155 m amsl using a Geometrics ES-3000 seismograph.

Figure 5. *Location of coffer dam, Cell C-2, within the cellular dam system (September 19, 2016). The 18-m diameter coffer dam is in the process of being tremie grouted with a cement-grout mixture subsequent to the crosshole work (September 2015).*

Seismic events were triggered with a Ballard Shear Wave Energy Source. To create a seismic event, water was bailed out of the 3 source borings (T1, T2, and T4). Triggering of the downhole source occurred at five shot elevations; 155.8, 152.2, 149, 145.6, and 142.2 m amsl (Figure 8). The seismic events were recorded and post-processed using Geogiga XW Tomo 8.0. These data were then inverted to obtain the associated *p*-wave velocities and used to create tomographs (Figures 10 and 11).

Seismic methods rely on acoustically quiet areas and are negatively impacted by surrounding noise. The flowing river and water rushing into the coffer dam did not provide an ideal testing site and may have interfered by camouflaging the first arrival times of the *p*-wave. To maximize the signal to noise ratio numerous stacks of the data were acquired at each shot location.

Analysis

Six profiles were collected within Cell C2 of the Kentucky River Lock 8 site. The profiles imaged the *p*-wave velocity of 14 m of the subsurface from elevations 142 to156 m amsl. Boring logs indicate the top of limestone to be at approximately 152.4 m asml. Of the 6 profiles

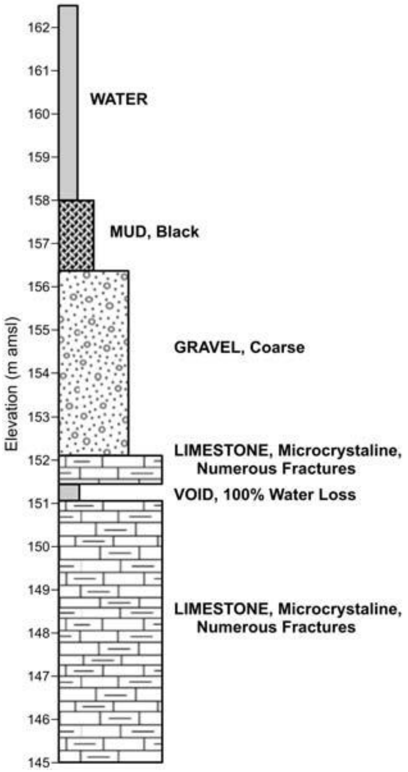

Figure 6. *Stratigraphic column from boring B-13.*

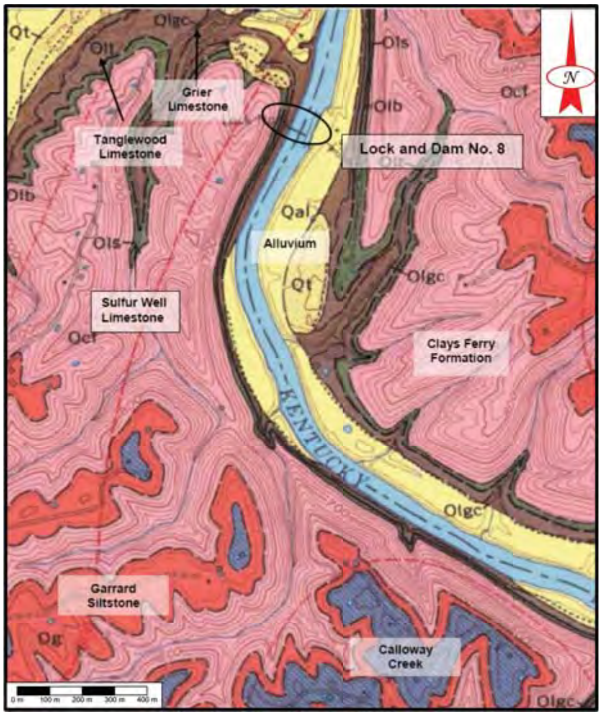

Figure 7. *Geology in the vicinity of the Kentucky River Lock and Dam 8 (Walcott, 1970).*

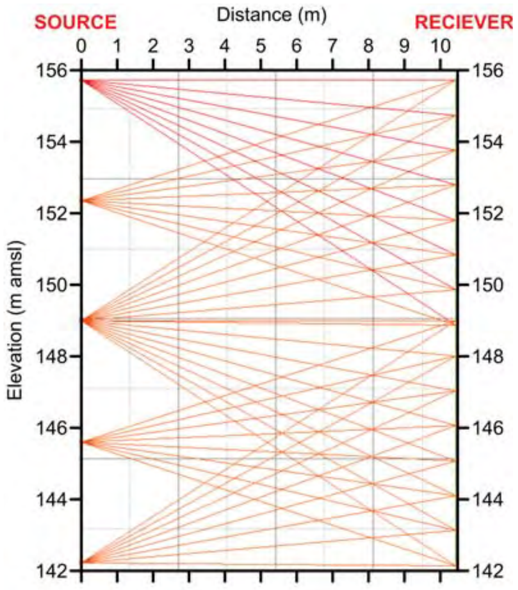

Figure 8. *Source to receiver raypaths for the first arrival of the p-wave energy.*

collected, the *p*-wave velocities range from 3,500 m/s to 6,000 m/s, consistent with the velocity of limestone. Velocities greater than 5,000 m/s (yellows and reds) are interpreted to be competent bedrock. Lower velocities, values less than 5,000 m/s (blues and greens), are considered weathered/fractured zones (Figures 10 and 11). The lower velocities above the top of the limestone (152.4 m amsl) reflect the poorly consolidated conglomerate and engineered materials used to stabilize the floor of the coffer dam. Data appear to be consistent in profiles sharing the same boreholes as the tightness of the velocity contours correlate well within a few hundred m/s.

T1–T4

Profile T1–T4 exhibits lower *p*-wave velocities throughout and is interpreted as heavily fractured and weathered. Boring B-13 is offset approximately 1.4 m to the southwest at position 4 m along the profile (Figure 10). The anomaly encountered during the drilling of B-13 is present within this tomograph, indicating that the void is at least 1.4 m wide and 7 m long. A low velocity zone at the base of the tomograph probably represents vuggy conditions associated with the fracture noted on tomograph T3-T4.

T3–T4

Profile T3–T4 shows lower *p*-wave velocities above the top of the limestone at 152.4 m amsl associated with the coarse gravel and engineered fill (Figure 10). A frac-

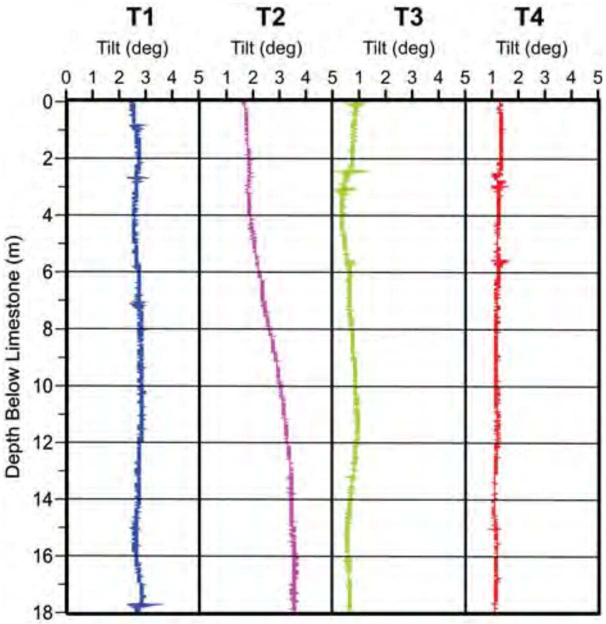

Figure 9. *Borehole orientation with respect to neighboring borehole.*

tured/weathered zone is depicted in the tomograph from between elevations 142 to 148 m amsl.

T3–T2

Profile T3–T2 also exhibits lower *p*-wave velocities above the top of the limestone (Figure 10). This site also shows a potentially fractured/weathered zone that is better displayed on tomograph T2–T1. Competent rock is inferred as the green to red color contours surrounding this low velocity zone.

T2–T1

Profile T2–T1 also exhibits lower *p*-wave velocities above the top of the limestone (Figure 10). A potentially fractured/weathered zone exists between position 0 m to approximately position 2 m and occurs between elevations 144.3 to 146.3 m amsl. Competent rock is inferred be represented by the green to red color contours surrounding this low velocity zone.

T2–T4

Profile T2–T4 crosses the site for a distance of 15 m, which is a long distance for a seismic event to travel without the seismograph recording noise (Figure 11). A small, potentially fractured/weathered zone is present between positions 12 m and 15 m and at an elevation of between 146 m and 148.5 m amsl. This zone may represent vuggy conditions.

T1–T3

Profile T1–T3 exhibits lower *p*-wave velocities throughout and is interpreted as heavily fractured and weathered. This profile is oriented parallel to the strike of the fracture and does not show up well (Figure 11). Boring B-13 is offset from the profile approximately 2 m to the northeast at 4 m along the profile.

Conclusion

A total of 6 crosshole tomographic profiles were collected inside the Kentucky River Lock 8 Cell C-2. The seismic data indicate a fracture zone that displays lower *p*-wave velocities in contrast to the surrounding material within the survey area. Profiles T1–T4 and T1–T3 are closest to B-13 and show low velocities throughout, indicative of heavily weathered zones.

The fracture zone strikes N1°E and dips 30°W (Figure 12). Hatton (2018) reported strikes of fractures in

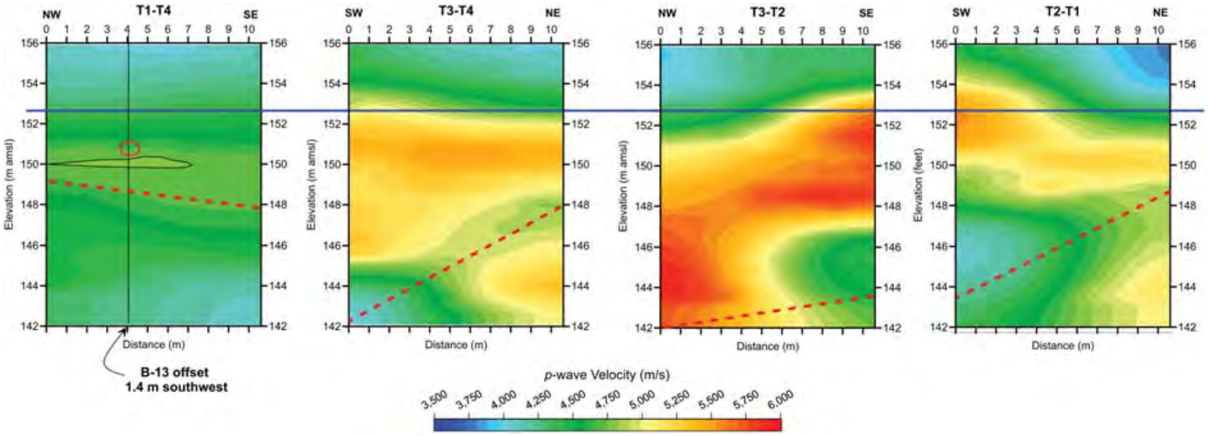

Figure 10. *Crosshole p-wave velocity tomographs between each cased boring showing top of limestone (blue line); possible void (thin black line on T1–T4) below projected B-13 void (red circle); and fracture (red dashed line).*

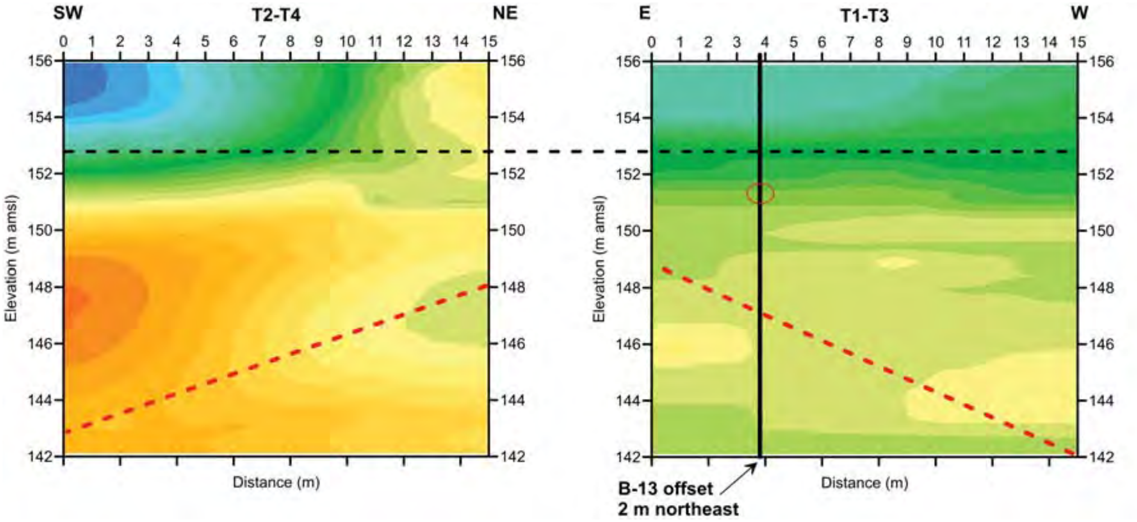

Figure 11. Crosshole p-wave velocity tomographs between each cased boring showing top of limestone (black dashed line); projected B-13 void (red circle); and fracture (red dashed line). Velocity color scale is shown on Figure 10.

surface measurements with orientations of between N4°W to N11°E, consistent with the results presented here. The fracture zone is inferred to be 1 meter wide and may not be present below 142 m amsl.

Cell C-2, a steel-pile coffer dam, was filed with a cement-grout mix prior to the installation of the secant wall. After curing, a series of overlapping grout-filled borings that represent the secant wall were installed vertically into the cement-filled coffer dam. Additionally, several grout-filled borings were installed 1 m on either side of the secant wall alignment at an angle of 15° (from the vertical) to the right or left of the wall. The purpose of the secant wall is to decrease the flow of groundwater through the formation as water flows downstream. The flow of water through the formation could destabilize the dam. Clearly the secant wall, as installed, will decrease the potential for groundwater to seep through the dam.

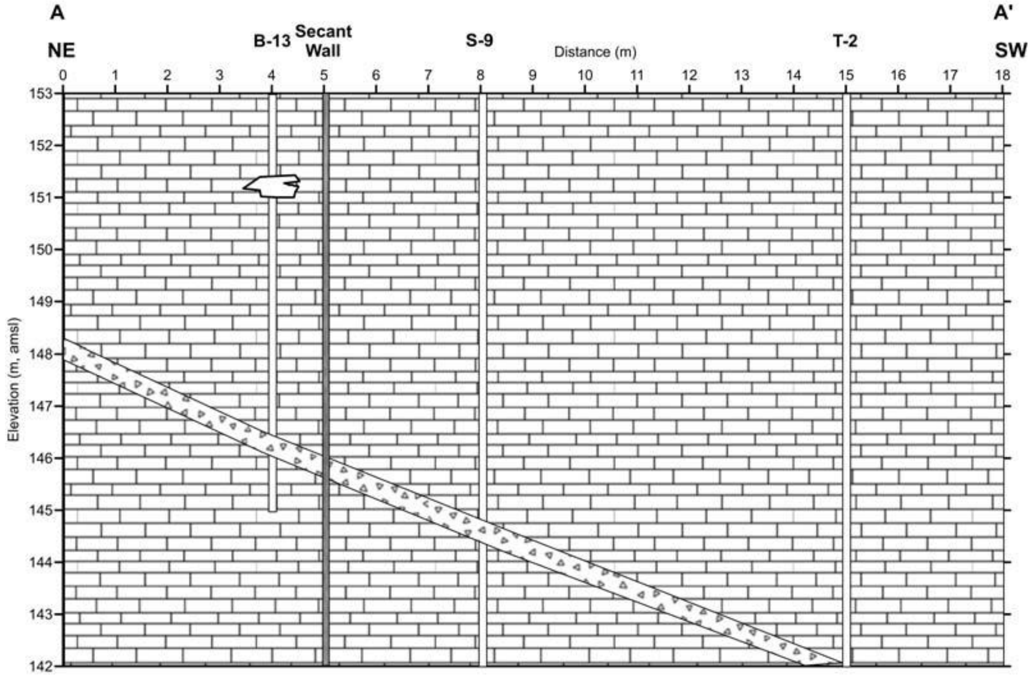

Figure 12. Cross section A-A' showing the relationship of the secant wall to the fracture zone (see Figure 4).

Seismic methods rely on acoustically quiet areas and are negatively impacted by surrounding noise. The flowing river and water rushing into the cell did not provide a quiet environment for the survey and may have interfered by camouflaging the first arrival times of the *p*-wave. It is recommended to ground truth the seismic data, particularly in the interpreted weathered/fractured zones.

Acknowledgements

The authors are grateful for the help provided by Stantec and Mr. Hatton.

References

Hatton RC. 2018. Performance of the Grout Curtain at the Kentucky River Lock and Dam No. 8. Master's Thesis submitted to the University of Kentucky.

Morisen KL. 2004. Structure of the Lexington and Kentucky River Fault Systems: Implications for the Kinematics of a Foreland Basin. GSA Abstracts V36(2), p. 74.

Reynolds JM. 1997. An Introduction to Applied and Environmental Geophysics: New York, NY, Wiley, 343 p.

U.S. Army Corps of Engineers, Louisville District, 1999. Environmental Baseline Study (EBS) for Finding of Suitability to Transfer (FOST) Kentucky River Lock and Dam No. 8.

Vanarsdale RB. 1986. Quaternary displacement of Faults within the Kentucky River fault system of east-central Kentucky; GSA Bulletin V97(11); pp. 1382–1392.

Welshans A, Dingrando JS, Gilbert DA. 2011. Geotechnical Study and Existing Conditions Kentucky River Lock and Dam Number 8, Gerrard and Jessamine Counties Kentucky. Proprietary report prepared by Stantec Consulting Services for the Kentucky River Authority, 81 p.

Wolcott DE. 1970. Geologic Map of the Buckeye Quadrangle Central Kentucky; US Geological Survey, Washington, DC.