INVESTIGATION OF SOURCE OF SEEPS BENEATH EARTHEN DAM, CENTRAL MASSACHUSETTS

Mario Carnevale, Hager GeoScience, Inc., Woburn, MA
Jutta L. Hager, Hager GeoScience, Inc., Woburn, MA
Robert A.S. Buller, Hager GeoScience, Inc., Woburn, MA

Abstract

Along with design and construction issues related to earthen dams, seeps have been implicated in numerous dam breaches. Geophysics is one technique that can be used to identify areas of possible existing "water seeps" and other high permeability zones within or beneath existing dams. HGI performed such an investigation ad a dam in central Massachusetts using a combination of seismic and GPR methods. Close to 7300 linear feet of GPR and 700 linear feet of MASW data were collected during the survey.

In order to provide the greatest resolution and to ensure sufficient signal penetration depth, a multiple frequency GPR program was implemented using 200-, 100-, 70-, and 40-MHz antenna systems. The MASW seismic method was used to obtain data for analyzing the Vs anomalies of soil layers and to provide stratigraphic information to constrain the GPR interpretation, including that for bedrock.

The geophysical survey identified areas of possible shallow and deep seepage both within and beneath the dam. These areas were further investigated during a borehole phase of the project. A stratigraphic analysis was also completed to assist in the dam remediation analysis. Till, bedrock surface trends, and other horizons were mapped along the length of the dam.

Anomalous shallow seepage zones were detected at a number of locations along the survey traverses, as well as deep seepage potential at and above the bedrock surface. Additional anomalies of interest included a possible former stream channel beneath the dam and an area with a high concentration of boulders.

Introduction

Geophysical methods are important tools for investigating seeps at earthen dams, as these have been implicated in numerous dam breaches and levee failures (Carnevale et al., 2004; Hager et al., 2005; Hollema & Olson, 2004; Miller et al., 2004). Geophysics provides a non-intrusive method to identify areas of possible existing seeps and other high permeability zones within or beneath existing dams.

HGI performed such a geophysical seep investigation of an earthen dam in central Massachusetts (Figure 1). Areas identified as possible existing "water seeps" and other high permeability zones within the dam would be included in a follow-up borehole investigative phase of the project. HGI's investigation also included a stratigraphic analysis to assist in the dam remediation analysis. Till, bedrock, and other stratigraphy were targeted for mapping along the length of the dam.

Based on existing borings, topographic data, and the primary survey objective, a geophysical investigation plan was designed using primarily ground penetrating radar (GPR) and surface wave seismic (MASW) methods.

Figure 1: Subject of geophysical investigation viewed from reservoir side.

Technical Approach

The multiple frequency GPR program was designed as the primary method because of its capability to resolve multiple issues, including permeability zones within the dam, the base of the dam, and subsurface stratigraphy.

The exact depths and lateral extents of the existing seep zones were unknown and assumed to be variable along the dam length. In order to obtain the best resolution and ensure sufficient signal penetration depth, data were collected using 200-MHz, 100-MHz, 70-MHz, and 40-MHz antenna systems.

The multi-channel analysis of surface wave (MASW) seismic method was used to obtain data for analyzing the Vs anomalies of soil layers, as well as to provide stratigraphic information to constrain the GPR interpretation, including that for bedrock.

Resistivity data collection was attempted in order to provide additional data. However, excessive tip resistance due to resistive surface sand in the available survey areas limited the usefulness of the data, and the survey was not performed.

Data Acquisition

Figure 2 shows the locations of the geophysical traverses completed for the investigation. The GPR and seismic survey geometries were designed to accommodate the survey area constrained by the narrow width of the road. All geophysical data was referenced to a 0+00 to 7+00 Station line established by the client along the top of the dam.

Figure 2: Topographic map of earthen dam and surrounding area showing locations of GPR (red) and MASW (light blue) traverses.

GPR Survey

GPR data were collected using a Geophysical Survey Systems, Inc. (GSSI) SIR 2000 digital acquisition system. The GPR data were displayed on a color monitor for immediate visual inspection and quality control and simultaneously recorded on the system's hard drive for later processing and interpretation.

A combination of 200- and 100-MHz monostatic and 70- and 40-MHz bi-static antenna systems were used for the subsurface investigation. Table 1 shows the setup parameters for the different antenna frequencies.

Table 1: GPR Survey Parameters

Antenna Frequency (MHz)	Range (ns)	Scan Rate (scans/sec)	Scan Rate (scans/ft)	Sample Rate (Samples)	Approx. Depth (feet)
200-monostatic	350	120	28	512	20-30
100-monostatic	700	16	12	1024	75-80
70-bistatic	700	16	12	1024	75-80
40-bistatic	800	16	12	1024	85-90

GPR data collection using the monostatic 100- and 200-MHz antennas was performed within a 700 x 18-foot survey grid established on the paved road along the top of the dam, which was oriented in an east-west direction (Figure 3). Data were collected with both antennas along east-west lines spaced 9 feet apart parallel to the dam crown and along north-south lines spaced 50 feet apart perpendicular to the crown. The 70- and 40-MHz frequency data were collected along east-west lines parallel to the crown only, since the restrictive north-south width of the road prevented obtaining sufficient data in that direction for stratigraphic characterization (Figure 4). In total, 7270 linear feet of GPR data were collected.

Figure 3: GPR data collection using the 100-MHz monostatic antenna in survey wheel mode.

Figure 4: GPR data collection using the 70-MHz bistatic antenna in survey wheel mode.

MASW Seismic Survey

MAW data were collected along one line on the north side of the paved road along the top of the dam. The MASW seismic line (Figure 5) used 48 geophones spaced 3 feet apart, for a total spread length of 141 feet. A common shot offset configuration was used with a 15-foot shot offset and 3-foot line moves.

Figure 5: MASW seismic line setup showing land streamer array with ATV.

Data were collected using 4.5-Hz OYO geophones configured in a land streamer array. The geophone array was attached to a Geometrics Geode® 48-channel exploration seismograph unit. An ATV-mounted 90-pound propelled energy generator (PEG) produced the seismic energy. A total of 235 shot gathers (234 moves for 702 feet) were collected. The quality of the seismic signals was verified in the field at each shot location.

Data Reduction and Analysis

Following the field data collection, the geophysical data were downloaded to a PC at the HGI office, where they were archived, processed, and analyzed using the following proprietary software:

- GPR: GSSI's RADAN for Windows XP™ with Structural and Stratigraphic Interactive Interpretation Module®
- MASW: Kansas Geological Survey's SurfSeis®
- Grid Modeling: Surfer® 8.0
- Graphic Presentations: Surfer® 9.0, AutoCAD® 2000

GPR Survey

The overall GPR signal quality was good, with changes in signal quality related mainly to the presence of possible utilities and changes in soil conditions. Some processing was required to reduce the detrimental effects of random noise and reflections from surface structures and buried debris. Band-pass filters, horizontal smoothing, background removal, gain adjustments, wavelet deconvolution, and migration were performed as essential processing steps.

Anomalies related to soil conditions were identified in the radargrams and recorded as distances along each traverse. The locations of GPR anomalies were plotted on an AutoCAD drawing base map created from HGI's GPS locations and the PDF file provided by the client (shown in blue on Figure 6). Figure 7 shows an example of the radargram anomalies.

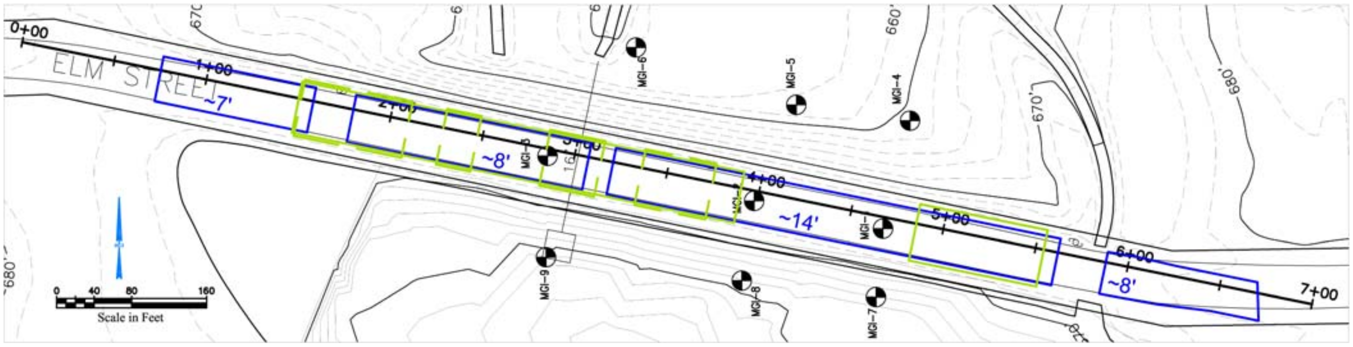

Figure 6: AutoCAD plot showing the locations of GPR (dark blue) and MASW (green) anomalies.

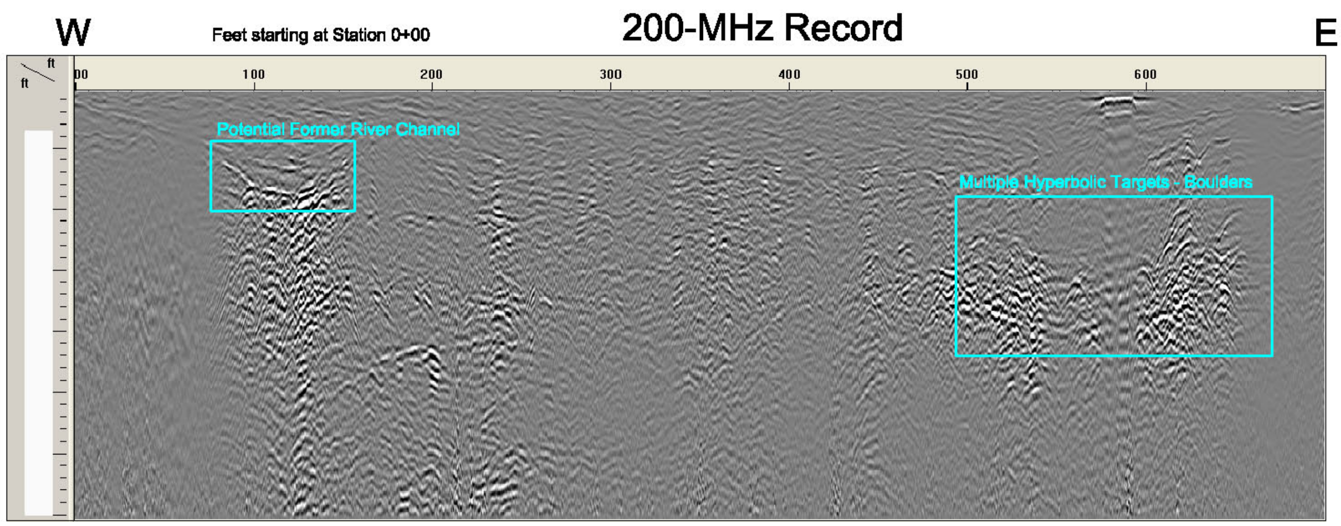

Figure 7: Portion of a 200-MHz GPR record showing the locations of anomalies correlated with stratigraphic sources.

MASW Seismic Survey

MASW data were downloaded to a PC for processing and analysis using the Kansas Geological Survey's SurfSeis software. The software was used to perform an overtone and dispersion analysis for each shot gather. The dispersion data were used in an inversion model to calculate a 1D shear wave velocity (Vs) profile at the mid-point of each shot gather. A 2D profile was then created from the 1D profiles by interpolating the mid-point values using a kriging algorithm.

Figure 8 is the 2D Vs profile for the MASW line, the location of which is shown on Figure 2 in light blue. As a multi-layered depth model of relative changes in Vs, anomalous changes in Vs can be interpreted as either natural or anthropogenic features, or a combination of the two. As noted in the caption to Figure 6, the anomalous changes in Vs at this dam site are identified in green. They represent the location and relative depth of Vs anomalies that may be associated with permeable soil or fractured rock.

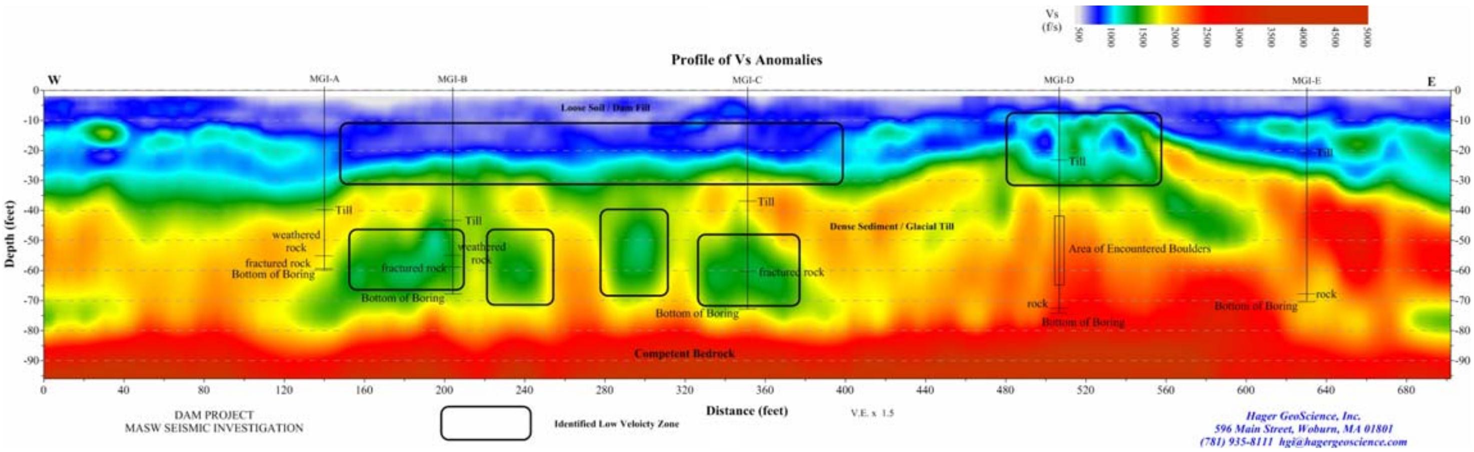

Figure 8: 2D Vs profile for the MASW line with low velocity zones boxed.

Conclusions

Complementary data sets from the multi-frequency GPR and MASW seismic investigation programs were combined to define both potential seepage in subsurface soils and soil stratigraphy. The correlation of GPR and MASW anomalies is highest between Stations 1+50 through 3+90 and 4+85 through 5+55, defining subsurface zones of saturated soils or fractured rock potentially related to the highest degree of seepage. Figure 6 also shows the locations of these anomalies referenced to the client's PDF base map. Figures 7 and 8 illustrate the identified GPR and MASW anomaly characteristics and locations, respectively. As noted on Figure 7, two areas of anomalous GPR signal response were interpreted as a possible former stream channel and boulders, respectively. The presence of boulders was confirmed by the log for an existing boring in this area.

In conjunction with the borehole information, the low Vs values observed in the MASW data suggest that the bedrock surface between Stations 1+40 and 4+00 is fractured and may constitute a permeable fault zone. It is reasonable to suggest that the fracture system is connected to the overlying saturated zone and can be a conduit for groundwater flow under the dam.

Figure 9, a composite GPR stratigraphic profile using signal reflections from multiple antennas, characterizes the subsurface stratigraphic trends. The bedrock surface (shown in black) shows an apparent dip toward the east and a bedrock valley that shallows in both directions away from Station 5+50. Till (shown in cyan) appears to be at its lowest elevation at Station 1+60 and shallows eastward. In some areas, the identified till reflector, calibrated from boring logs supplied by the client, displays a very low reflection amplitude and therefore creates a poorly defined reflector. In these areas, the till may change to a sandier composition that makes its precise depth difficult to determine. Where this occurs, the till horizon is shown as a dashed cyan line to indicate a lower confidence interpretation level.

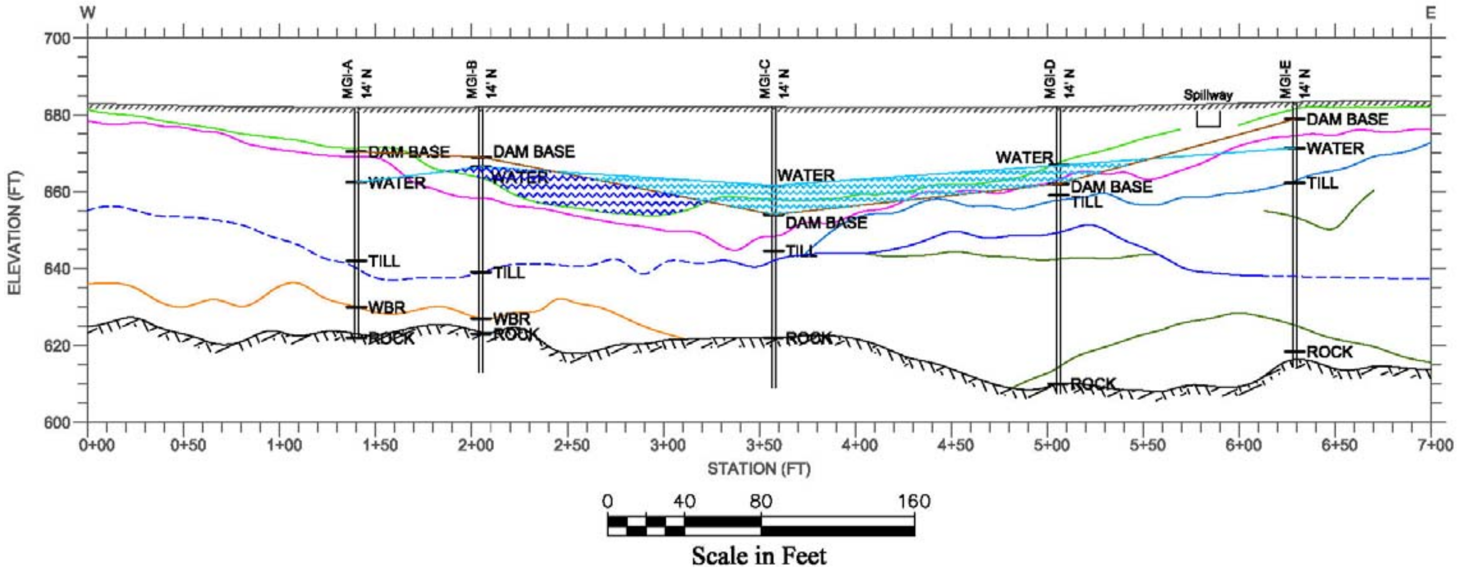

Figure 9: Composite GPR stratigraphic profile along the surveyed dam calibrated from existing borings.

In addition to the bedrock and till horizons, Figure 9 also shows the relationships of the base of the dam and other stratigraphic horizons to the water table. These relationships suggest that seeps from the base of the dam should occur between Stations 1+90 and 5+54. Seeps on either side of these stations would be within naturally occurring sandy till or continuous pockets or lenses of coarse glacial sediment.

Based on the results of the geophysical and drilling investigations, we conclude that the seepage potential at the investigated dam has both a shallow and a deep component. The potential shallow seepage is associated with loose and saturated dam fill. Figure 9 illustrates where the unconfined groundwater table intersects the dam fill material (hatched areas). The light blue hatch illustrates the saturated fill based on boreholes only. The dark blue hatch illustrates the saturated zone based on boreholes and GPR interpretation. Figure 10, a combined MASW and GPR profile, shows low Vs within the potential shallow seepage zone (black rectangular callout from Station 1+50 to 4+00) ranging from approximately 500 fps to 700 fps.

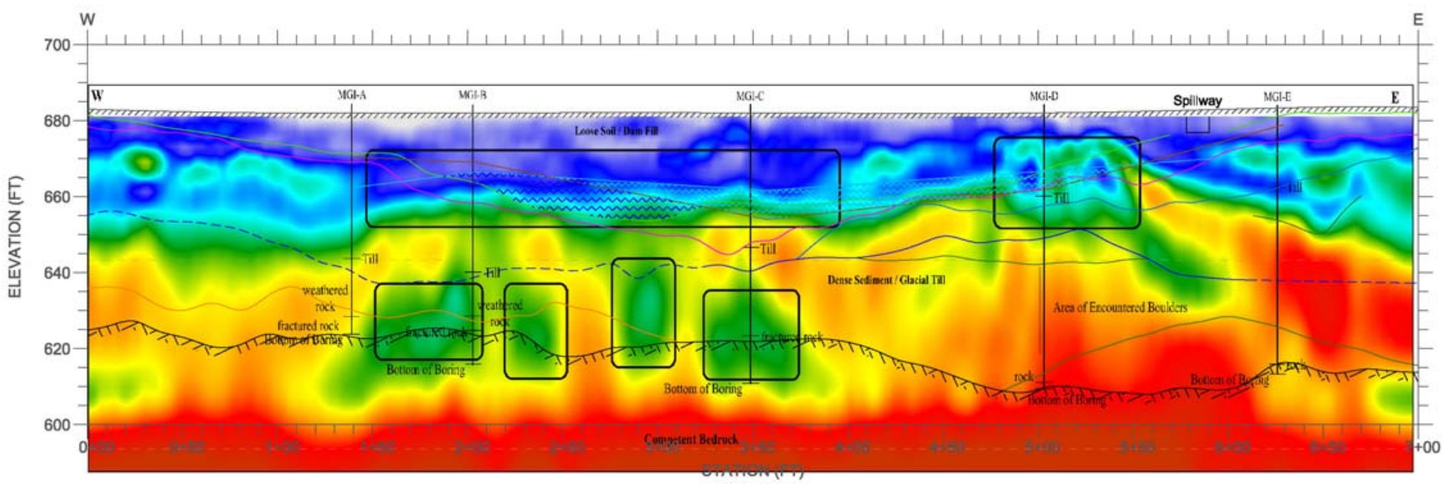

Figure 10: Composite GPR and MASW profile showing Vs, bedrock, and stratigraphic horizons.

The potential deep seepage zone is shown in Figure 10 as relatively low Vs zones (4 black rectangular callouts) within higher Vs bedrock and till. The potential seepage zones straddle the fractured bedrock surface and overlying till.

The geologic association of the potential deep seepage is based on potential bedrock fracture zones (faults) and meandering stream positions throughout post-glacial history. Sandy till and spatial variations of sand and gravel (outwash) deposits are the result of stream channel migration during the post glacial period.

References

Carnevale, M., and Hager, J., 2008, Combined ground penetrating radar and MASW surveys to locate dam seeps, Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems, 997-1006.

Carnevale, M., and Hager, J., 2008, Characterization of a beach revetment using ground penetrating radar and MASW, Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems, 795-804.

Hager, J., Carnevale, M., and Jones, B.R., 2005, Unconventional deep-water GPR investigation of drilling obstructions, Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems, 757-764.

Hollema, D.M., and Olson, L.D., 2004, Application of a combined nondestructive evaluation approach to detecting subgrade voids below a dam spillway, Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems, 1059-1070.

Miller, R.D., Ivanov, J., Hartung, S., and Block, L., 2004, Seismic investigation of a sinkhole on Clearwater Dam, Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems, 1082-1098.

Sack, D.A., Olson, L.D., and Yarbrough, H.A., 2007, Nondestructive techniques for inspecting concrete dams and spillways, Hydro Review, August, 42-49.