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On the Cover

Wolf Creek Dam is on the Cumberland River in South Central Kentucky near Jamestown, Kentucky. It provides flood control, hydropower, recreation, water supply, and water quality benefits for the Cumberland River system. Construction began in 1941 and was interrupted by WWII from 1943 to 1946. The reservoir was impounded in December 1950. The 5,736 foot-long dam is a combination earthfill and concrete gravity section. U.S. Highway 127 crosses the top of the dam.

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- Fostering dam technology for socially, environmentally and financially sustainable water resources systems;
- Providing public awareness of the role of dams in the management of the nation's water resources;
- Enhancing practices to meet current and future challenges on dams; and
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USING GEOPHYSICS TO EVALUATE AN EMBANKMENT DAM SINKHOLE

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ABSTRACT

Located near Knoxville, Tennessee, Chilhowee Dam is 80 feet high and 1,500 feet long with two embankment sections, a concrete gated spillway, and two concrete non-overflow sections. A six-foot deep sinkhole formed near the left abutment on the upstream slope of the Chilhowee Dam's embankment in February 2000. Geotechnical investigations were performed to evaluate the sinkhole, including borings, test pits, instruments, and geophysics. The dam posed two distinct challenges to a geophysical investigation: 1) a very complex geometry of the embankment with upstream sloping clay core, many filters each side of the clay, rockfill shells, and a steeply sloping rock foundation contact; and, 2) restrictions from the hydro power generation at the dam. The focus of this presentation is the multiple surface geophysical methods used for subsurface evaluation to help determine dam remediation.

Two geophysics methods were used: 1) Self-potential (SP) survey to evaluate dam seepage, and 2) three dimensional (3D) seismic refraction survey to evaluate the extent of soft clay found in previous borings. The seismic investigation used an innovative 3D refraction technique to evaluate the internal embankment materials, and represents to our knowledge the *first* refraction data set ever collected, processed, and presented in full 3D format at an existing dam.

SP results indicated two distinct preferential flow paths through the embankment. One of these flow paths crossed the sinkhole, the other was adjacent and near parallel.

Geophysics results and conclusions were used together with results of geotechnical investigations, embankment design and as-built information to make engineering evaluations of dam safety, the impact of the sinkhole, and extent of remediation.

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INTRODUCTION

Chilhowee Dam is located near Knoxville, Tennessee on the Little Tennessee River. It was constructed in 1957, and is 80 feet high and 1,500 feet long with two rockfill embankment sections, a concrete gated spillway, an integral powerhouse, and two concrete non-overflow sections (Figure 1).

Figure 1. Aerial Photo of Chilhowee Dam Identifying Sinkhole Location and Geophysical Survey Location (Photo source: Google Maps)

The south (left) embankment is 405 feet long. The embankment has an upstream sloping clay core with granular filters, 2 upstream and 3 downstream, and rockfill shells. The design clay core width is 10 feet at the top and widens with depth. The upstream slope of the clay core becomes shallower about 21 feet below the crest. The dam is founded on rock, which consists of conglomerate, sandstone, and siltstone. The rock in the core trench was consolidation grouted with 10 foot deep holes at maximum 10 foot spacing. A single-row grout curtain was constructed to a depth of 24 feet in the center of the core trench with holes spaced at 10 foot intervals. A cross section of the dam showing these features is presented in Figure 2.

As-built embankment construction deviated from design above El. 862. The design has steep to vertical planar boundaries between filters and at the clay core to filter boundary. The as-built upstream boundary between the fine filter and the clay core formed a “Christmas Tree” configuration, with a lens of fine filter sand extending into the clay core at each lift.

On the downstream side, the filter boundaries slope either upstream or downstream at the angle of repose of the material, alternating in a herringbone pattern for each lift. These patterns are shown in Figure 2.

Permanent surface monitoring points installed throughout the embankment and measured since original dam construction in 1957 indicated an increased settlement rate starting in 1988 at two monitoring points near the sinkhole.

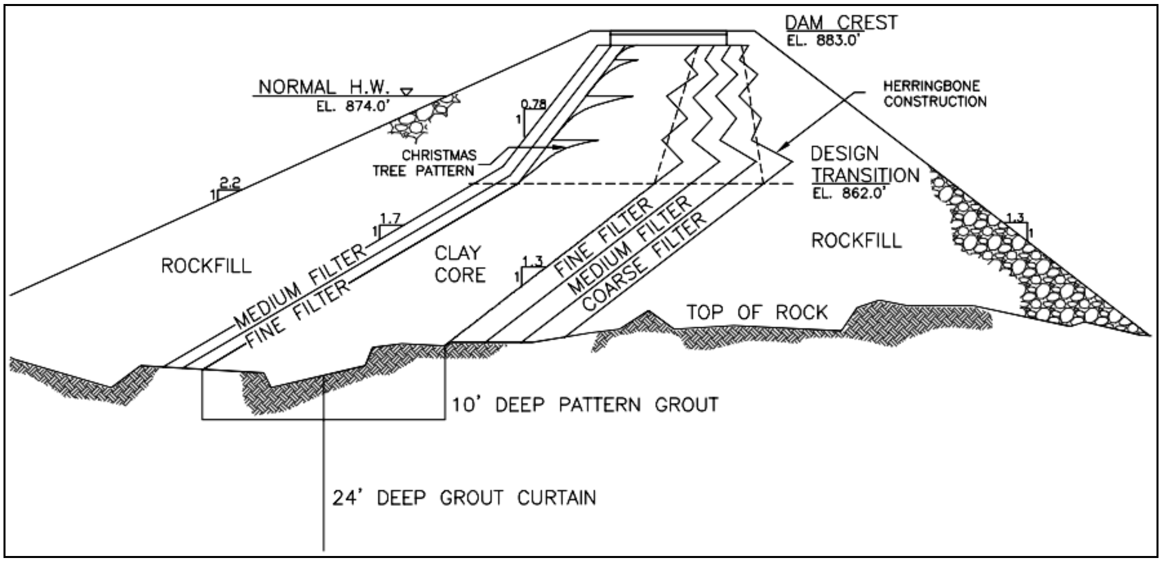


Figure 2. Cross Section of Chilhowee Dam

In February 2000, a six-foot deep sinkhole formed in the embankment near the left abutment at the intersection of the crest and upstream slope. The location of the sinkhole is shown in Figure 1.

A shallow depression was first noticed in the embankment next to the crest pavement during a routine inspection in 1996 at the intersection of the upstream embankment slope and the crest, near the left abutment. It suddenly developed into a sinkhole about 6 feet deep and up to a foot wide in February 2000. The sides of the sinkhole formed a narrow neck shaped void. It was nearly vertical and had stones protruding irregularly from the sides; a tape measure could not be advanced beyond 6 feet deep. This prompted the subsurface investigations described below that were performed from 2000 to 2007.

By 2008 the sinkhole had grown to a shallow cone shaped depression with an 8 foot diameter. The middle of the cone did not have a void, but was about 2 feet lower than the surrounding rim, with crushed stone covering the ground surface. A guard rock centered at the depression disappeared below surface, settling more than 4 feet in a stair step function since the test pit was backfilled in 2000.

BACKGROUND

A subsurface exploration program was performed in March 2000 just after the sinkhole first developed. It included 6 borings to investigate the condition of the clay core downstream of the sinkhole. All borings extended through the clay core and reached rock. Clay core materials were classified as CH to CL. The borings found that the contact between the upstream filters and clay core was steeper and further downstream than the design drawings indicated, the clay was soft below the reservoir level with SPT blow counts often 4 or below, and that upstream fine filter sand lenses extended several feet into the clay core.

A 9 foot deep test pit, centered at the depression, was excavated in March 2000 to the reservoir level extending several feet downstream into the clay core. The clay core was found intact, although the upstream filter sand extended as horizontal lenses several feet into the clay core, and some of the clay was soft. The excavation was backfilled restoring the surface to original grade. There was no evidence of piping or clay core fractures. The sinkhole void could not be found at the bottom of the test pit, or in the borings.

Settlement monitoring points were installed surrounding the center of the sinkhole. A dye test was performed at the sinkhole in October 2005 to evaluate if seepage was occurring rapidly through or under the clay core. No dye was found exiting the embankment.

Three subsurface exploration phases were conducted in 2006 and 2007. The first phase consisted of two observation wells installed in the rock downstream of the sinkhole. Permeability tests were conducted and a borehole camera was used to determine that clay core material was not migrating through the rock joints.

The second phase consisted of subsurface exploration using the geophysics described herein, which was conducted in summer and fall of 2006.

The third subsurface exploration phase, completed in June 2007, consisted of borings in the upstream crest of the south embankment. It was developed to evaluate subsurface conditions near the sinkhole to confirm the seepage zones identified by the geophysics. Sand lenses were found in the upstream limits of the clay core, but they did not extend through the clay core.

GEOPHYSICS

Goals

The engineering goals for the geophysics near the sinkhole were: 1) find the location, width, and depth of any unusual seepage paths in, through, or beneath the embankment; 2) define the lateral and vertical extent of soft clay in the embankment core; and 3) find any anomalous dam foundation bedrock conditions.

To achieve these goals two nationally prominent geophysics firms were selected to meet at the site, review the embankment geometry, and evaluate the geophysics methods that could be used. The initial meeting included review of embankment design drawings and as-built drawings. A site visit was made to the sinkhole to review site conditions and evaluate restrictions, such as the steep upstream and downstream rockfill slopes, the steeply sloping bedrock surface, the close proximity of the reservoir to the sinkhole, crest pavement, grounding grid cables that crossed the sinkhole area, overhead transmission lines, the nearby switchyard and powerhouse, sloping clay core and filters, and the rock cliff next to the abutment.

Possible geophysical methods that could be used to achieve the engineering goals were selected at this meeting where the advantages and disadvantages for each method in achieving the goals were discussed. It became evident that the two best methods to achieve the engineering goals were Self-Potential (SP) for evaluating seepage conditions and Seismic Refraction to assess the material strength and stiffness variability in the clay, sand filters and rock foundation.

Methods

Both normal pool (El. 874) and low pool (El. 869) SP surveys were performed to better define the background noise and to better identify the depth of the potential seepage zones. The low pool SP survey was conducted with the reservoir 5 feet lower than normal pool, and was completed a few months after the normal pool survey.

The SP method involves the measurement of electrical potentials that occur within the earth, or embankment. These potentials, which can be measured at the ground surface, can be caused by both natural and artificial sources. In the embankment, the electrical potential of interest to be measured is caused by movement of ions in groundwater flowing through a porous media. However, other natural sources include oxidation-reduction associated with mineral deposits, high temperature gradients, and induced currents caused by magnetic storms. Artificial sources consist of corrosion potential associated with buried metal objects, and stray, transmitted, or induced potentials associated with buried utilities or nearby power lines. These other sources must be considered during data measurement, data reduction, and data interpretation.

The seismic survey was conducted using a state-of-the-art data acquisition system, and was performed to allow 3D modeling and results presentations. We believe this was the first application of true 3D seismic refraction data acquisition and modeling for an engineering application at a dam.

SP and seismic data were acquired, processed and interpreted independently. Both SP surveys and the seismic survey used the same surface positions, as shown in Figure 3.

Field Work

SP instrumentation consists of three simple elements: non-polarizing electrodes, high impedance voltmeters, and light weight, insulated connecting wire. Each element of the system was designed to minimize electrical noise in the data.

Data positioning for the SP measurement points was achieved using a real time kinematic (RTK) global positioning system (GPS) consisting of a base station receiver and a roving receiver. Measurement points are shown in Figure 3.

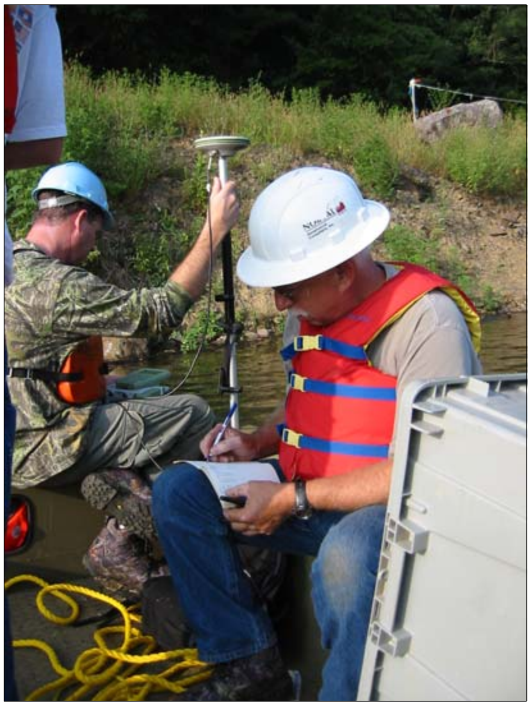
The field techniques used for SP data collection were designed to optimize data quality and production. During all SP measurements electrical generation was shut down at the powerhouse, and the subsurface grounding grid was disconnected because it is critical to eliminate spurious currents in and near the SP survey.

To measure the SP distribution at the ground surface, a base electrode was buried in the soil and the potential at this base station was arbitrarily defined as zero. A reel holding several thousand feet of wire was connected to the base electrode and hand carried to each measurement location, which were in a 10 foot by 10 foot grid on land. At each measurement location a second electrode was put in contact with the soil and connected through a digital high-impedance voltmeter to the wire reel (see left inset photo below). The potential between the base and measuring stations was then read on the voltmeter and recorded in a field notebook. This procedure was repeated until the potential values were mapped over the entire survey area.

Five electrodes were used to conduct the on-shore SP survey. One, referred to as the base electrode, was installed on the west edge of the widened paved area, approximately 50 feet west of the dam crest. Another electrode, referred to as the traveling or “measuring” electrode, was used to make the measurements at the data points distributed throughout the on-shore survey area. A third electrode was referred to as the reference electrode. Two electrodes (dipole) were installed at fixed locations at the north and south ends of the left embankment on the west side of the crest. These two electrodes were connected to a second voltmeter and a portable computer (PC) to monitor temporal variations (i.e., tellurics) in the electrical field. This dipole was used to determine whether or not any significant temporal fluctuations occurred during the course of the SP survey. The PC was programmed to record the potential between the two electrodes at 30-second intervals throughout each survey day. These data were used to measure electrode drift during the course of the survey, and the resulting data were used to correct the measured SP values for electrode drift.

The off-shore (in the reservoir) SP survey was performed similarly to the on-shore SP survey, but from a boat (see middle inset photo below), and using underwater electrodes. During the normal pool SP survey, the off-shore SP data were collected along traverses spaced about 20 feet apart and oriented approximately parallel to the dam axis, as shown in Figure 3. SP readings were taken at regular time intervals as the boat advanced along the traverses. Each traverse was conducted twice; first south to north, then north to south. GPS readings were taken during the survey.

For the seismic analyses, 120 channels were used to acquire sufficient coverage to surround the sinkhole area. That is, 120 14-Hz geophones were placed on the ground in a 10-foot by 10-foot grid, with all geophones recording each seismic energy source (see right inset photo). Geophone positions used the same locations that were occupied during the SP survey. A 16-pound sledge hammer was used on an aluminum block as the seismic source to impart an impulsive energy source. P-wave signals were generated when the hammer struck the aluminum block. The block provides good coupling to the ground and good transfer of consistent energy.



Photos: SP upstream embankment slope (left); SP off-shore (right); Seismic on crest road (bottom)

Data Reduction

SP data and drift readings were entered into a proprietary computer program along with the station locations at the end of each field day. The computer program corrected the SP readings for any drift in the measuring electrode and produced a table listing the corrected SP reading for each measurement location based on time of reading. For both the normal pool and low pool surveys, the on-shore and off-shore data were combined into a single data set and processed. This program used the data locations to generate a uniform grid covering the entire survey area. This resulting surface was then contoured using a 10 mV contour interval, producing the color shaded contour map shown in Figure 3 illustrating the aerial distribution of SP values. The SP program used was SPGEN, 1993, “A QUICKBASIC Program used for General Modeling and Interpretation of Self-Potential Field Data”, by Theodore Asch (prepared for the Bureau of Reclamation, Seismotectonics and Geophysics Section).

Although the SP contours indicate the general location and configuration of possible groundwater flow patterns, they provide little information on the depth of the groundwater flow. However, the depth of water movement along a preferred seepage path can be estimated using computer 2D modeling techniques. The program models groundwater flow using subsurface electrical charges in the form of a sheet, a line, or a series of points. The program uses an iterative forward modeling procedure through which the parameters associated with the chosen source type can be adjusted until a model SP curve is produced that reasonably matches the observed (field) values. At that point the program’s inversion routine is used to refine the model to produce an even closer fit.

For Seismic data reduction, the Geostructural Analysis Package (GAP) (3-dimensional discrete element modeling program, by Alan Rock, Summit Peak Technologies, LLC.) modeling starts with development of a 3D model space. Arrival times were picked using an automatic arrival time picker developed as part of GAP. Arrival time picking was accomplished for 14,856 ray paths, which represents 75% of the total possible ray paths between sources and receivers. The signals that were rejected were generally low amplitude, low signal-to-noise ratio, or early arrivals times. Records were gathered into what is called a “signal gather”; that is, all the seismic signals from a shot point are plotted beneath each receiver in the model space. There were 156 such shot gathers for this project, and they were each manually inspected to be sure the automatic arrival time picker correctly assigned the proper time for the first (refracted-wave) arrival. Signal conditioning was performed as part of the arrival time picking process, where the signals were filtered for their high-frequency content (i.e., a high-cut filter at 250 Hz), and a velocity filter at 15,000 ft/sec to avoid false picking of early arrival times. A high-cut filter was required to remove high-amplitude air-wave arrivals, particularly when the aluminum striking plate was placed on the crest pavement.

The 3D model used discrete 2-foot diameter spheres giving elements with a 2-foot resolution. The model contained 246,310 elements which had 2,864,508 velocity links (i.e., 12 links per element).

Using the discrete element method of modeling, GAP starts with a uniform, homogeneous average velocity model. The velocity was initiated at an average link velocity of 1,000 ft/sec; therefore each element had an initial average velocity of 1,000 ft/sec. The GAP model process starts with this low uniform velocity and converges toward a root-mean-square error of less than 10% to be considered a good solution.

RESULTS

SP Results

The SP contours indicated two areas of concentrated seepage, one at the sinkhole, designated Zone 1, and the other north of the sinkhole, designated Zone 2, identified as "Anomalous" seepage in Figure 3. Zone 1 extends through the area of the sinkhole and continues into an area that was assumed to be bedrock abutment. Zone 2 extends through the embankment and was interpreted to extend well downstream of the embankment. The normal pool SP survey indicated uniform, widely distributed seepage into the embankment and upstream left abutment, identified as "Normal" seepage in Figure 3.

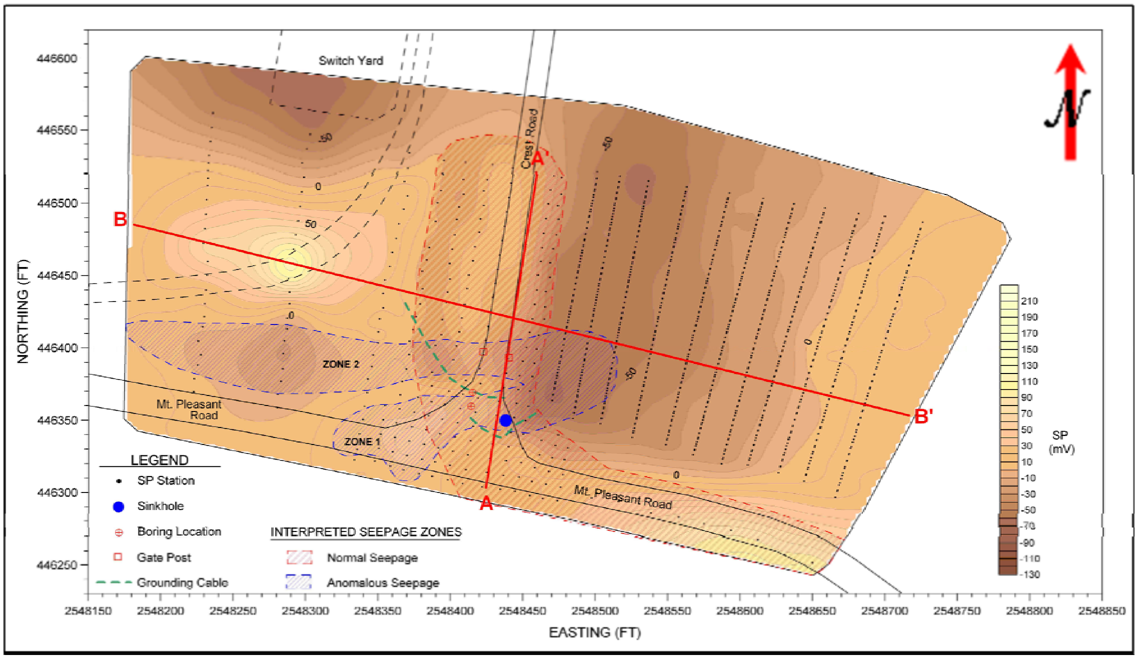


Figure 3. Normal Pool SP Results with Seepage Zones

Based on the normal and low pool SP surveys, Zone 1 is prominent at normal pool and reduced at low pool, although still extending through the sinkhole. The SP depth evaluations indicated a shallow seepage depth, which is consistent with the 5-foot reservoir level reduction from normal to low pool which reduced the seepage amount. Zone 2 was found at normal pool and was not found at low pool. This together with SP depth evaluations indicated a likely shallow seepage depth for Zone 2.

The quality of the SP data acquired during the normal and low pool surveys was quite good as evidenced by close repeatability of the measurements. This provides a degree of confidence in the data and the results.

Seismic Results

The GAP analysis successfully produced a 3D seismic refraction velocity model. Seismic velocities for the rock surface below the sinkhole (Sta. 14+75) were about 5,500 ft/sec, which was much lower than those beneath the abutment south of the sinkhole (Sta. 15+00) or 25 feet north of the sinkhole (Sta. 14+50), which were about 7,000 to 9,000 ft/sec. This indicates that rock is more weathered and/or fractured along Sta. 14+75 near the sinkhole than in the surrounding areas. This is consistent with the construction information showing significant rock excavation at Sta. 14+75, indicating poor rock that was excavated in 1957 in an attempt to reach sound rock in the core trench excavation.

A low seismic velocity trough was identified by the 3D modeling. It extended upstream to downstream through the sinkhole area, and through SP seepage Zone 1. Figure 4 shows a horizontal slice through the 3D velocity model at El. 875 and Figure 5 shows a vertical slice along the upstream downstream direction at Sta. 14+72. The low seismic velocity indicates low density material. This implies either poor compaction of materials during initial construction within the trough or that materials have become lower density since construction, possibly due to piping.

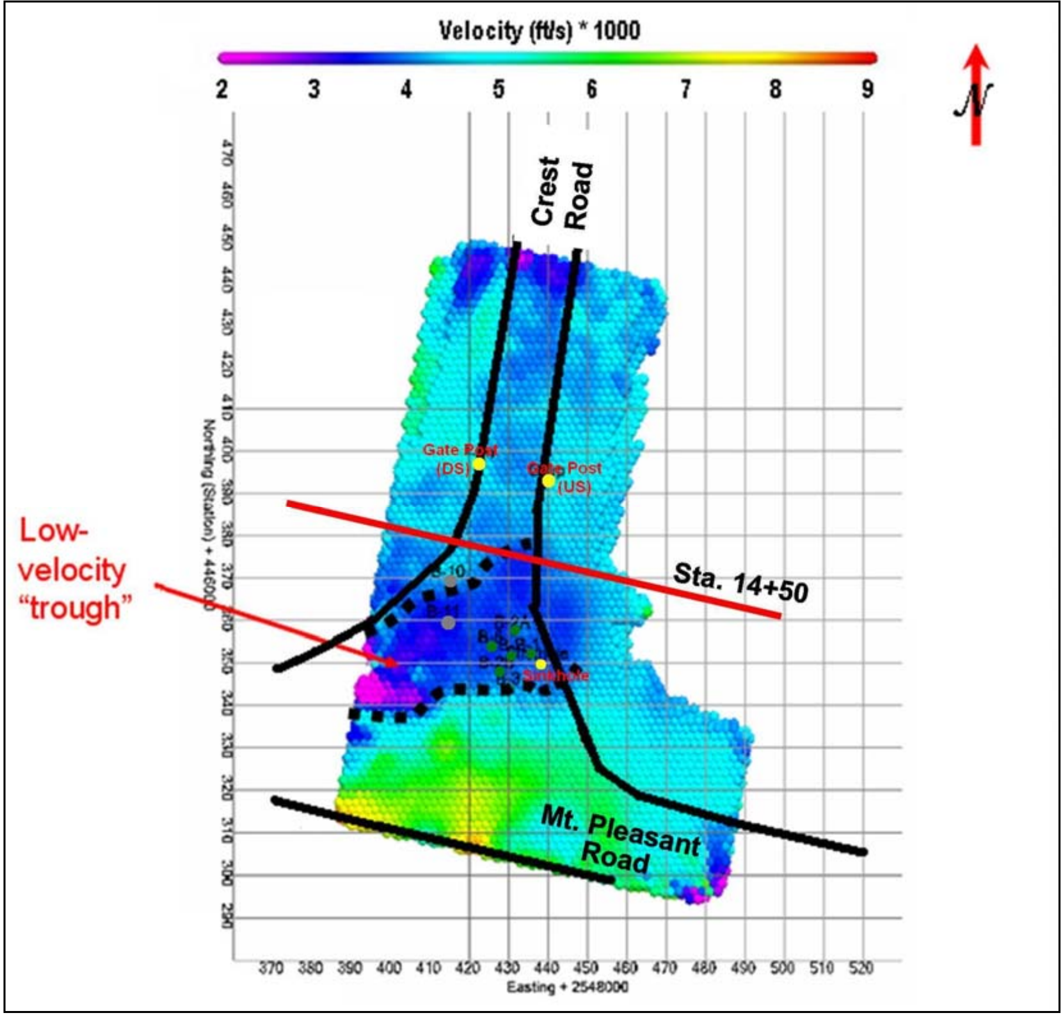


Figure 4. 3D Seismic Refraction Results, Horizontal Slice at El. 875.

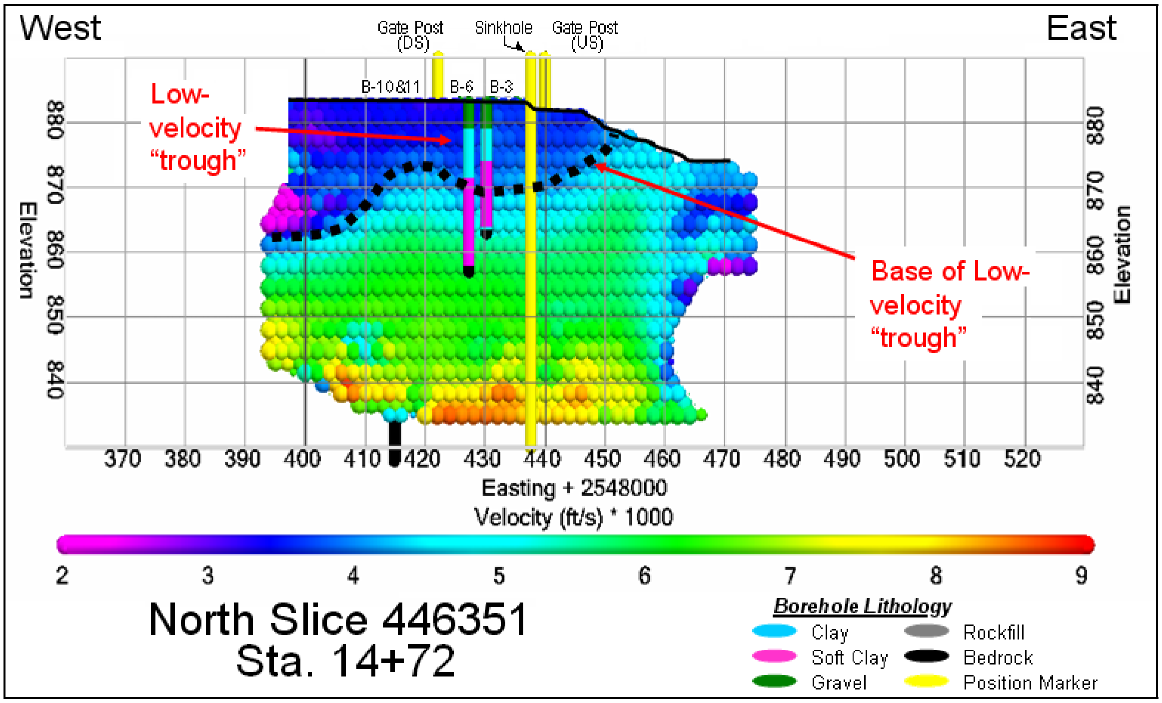


Figure 5. 3D Seismic Refraction Results, Vertical Slice US-DS at Sta. 14+72

Field Verification

Geophysics results should be verified by invasive methods such as borings, test pits, or excavations, which provide "ground truth." For this project, this ground truth was provided by the remediation construction of the sinkhole area. In September 2008, the sinkhole was carefully and slowly excavated in thin layers using the "follow the sinkhole method." Excavation was done with a smooth bladed backhoe bucket to avoid disturbing the soil at the base of the excavation. The engineer carefully evaluated the sinkhole position and size every few feet as the excavation progressed. This ensured that the bottom of the sinkhole would be found, and that any evidence of the cause of the sinkhole would not be destroyed during excavation. Using this method the cause of the sinkhole was discovered.

Some of the information developed from this excavation method also verified the geophysical survey results. In particular the following were observed:

1. Voids were found in the clay core; one air void was up to several cubic yards. Some collapsed voids were filled with loose crushed stone and very soft clay. The voids were within the limits of the seismic low velocity trough identified by geophysics (see Figure 4). And they were within the limits of Seepage Zone 1 identified by SP (see Figure 3).
2. A vertical crack in the clay core filled with crushed stone extended completely through the clay core upstream to downstream. This was within the limits of the SP identified Seepage Zone 1 and the seismic low velocity trough.

3. Top of rock was moderately to severely weathered along the upstream to downstream profile at Sta. 14+75, which was near the sinkhole, and the rock at Sta. 15+00 was less weathered. The seismic velocities found at Sta. 14+75 were much lower than the profiles along Sta. 15+00, supporting these observations.
4. Rock bedding was near vertical and the strike was in the direction parallel to SP Seepage Zone 1, nearly east-west. This would indicate that seepage flow followed the prominent jointing pattern, which was the bedding plane joint.
5. Loose material was found in the downstream rockfill portion of the embankment just downstream of the sinkhole where the embankment flares out to meet the abutment. The material consisted mostly of loose silty sand and gravel, with some cobbles and boulders. This loose material is within the limits of the seismic low velocity trough.

Successful Geophysics Procedures

Several procedures were developed for this project that allowed the geophysics to be successful. These are identified as follows:

1. **Develop Engineering Goals –** It is important for the owner's engineer to develop engineering goals for the geophysics that will be used to investigate subsurface conditions at a dam.
2. **Find Knowledgeable Geophysicists –** The engineer should find a knowledgeable geophysics firm that is eminently qualified and with extensive experience working on dam projects. For complex subsurface geometries, complex engineering goals, or where there is a dam safety risk, the team should consist of more than one qualified firm.
3. **Provide Subsurface Information –** The engineer should provide all existing subsurface information to the geophysics team(s), such as; boring logs, test pits, instrumentation data and installation logs, dam design drawings and specifications, and construction photos. Without this information, it will be difficult for the geophysics team to determine which geophysical survey method, or methods will be appropriate.
4. **Identify Site-Specific Impediments –** Every site has impediments that can prevent successful execution of a geophysical survey. During development of the geophysical methods and site visit activities, features that will affect data quality must be identified and the consequence of each discussed with the owner's engineer. The impact of cultural features such as electrical power generation, overhead or subsurface utilities, vibration energy, and traffic must be considered prior to deployment of a geophysical method.
5. **Develop Methods –** The engineer should meet at the dam site with the geophysics teams well ahead of the expected field work. Prior to this meeting, all available documents should be reviewed by the geophysics teams. The geophysics teams together with the engineer should determine which geophysical methods have the best chance of meeting the engineering goals. The goals and the likelihood for success should be summarized in a table and finalized during this meeting. Based on this table, the geophysical methods proposed to meet the

engineering goals should be determined. More than one method should be selected. This is to allow flexibility during field work if it becomes evident that a selected method is not providing meaningful data. Also, it is important to use methods that complement each other.

6. **Data Presentation –** It is important that geophysical results and conclusions be in engineering terms. They must be converted from geophysics terminology to meet the engineering goals, and allow the engineer to understand the geophysical results. This requires the geophysicists to understand the engineering significance of their work, and that their end product is not just data in geophysical units, such as seismic velocity, milligals, millivolts, etc. These tend to be the end product of many geophysical investigation reports, with conclusions that identify the range of the data, and no practical engineering evaluations or conclusions.

CONCLUSIONS

The following conclusions are offered:

1. **Non-Invasive Method –** Geophysics is a non-invasive subsurface investigation method that does not impact the dam or an impervious core of a dam. Therefore there is no risk of damaging the dam, such as there is with borings or other invasive methods, and it can be done with the reservoir at or near normal pool.
2. **Successful –** Geophysics was successful in identifying complex subsurface conditions, as verified during embankment repair excavation. A well planned geophysical investigation can provide both subsurface information and allow identification of anomaly targets for future investigations. The anomaly targets are more likely found if the “successful geophysics procedures” described above are followed.
3. **Good Value –** If the above “successful geophysics procedures” are followed; the geophysics has a good chance for success, which leads to a cost effective subsurface investigation. Results of the geophysical investigations were used to identify the approximate extent of the unusual zones (anomalies) associated with the sinkhole that required excavation remediation to fix. Additional borings made after the geophysics were used to help refine these limits.
4. **Confirm Results** – The “follow the sinkhole” method was essential for field verification of the geophysics results and the sinkhole, and to allow forensic determination of the cause of the sinkhole. The dam remediation work can then be done in confidence knowing the cause of the sinkhole, which in this case was due to piping of the clay core in a small area where the downstream fine filter was missing against the rock abutment.
5. **Seepage Investigation –** The SP method identified the seepage problems at the dam, in particular the piping which caused the sinkhole.
6. **Seismic Investigation –** The 3D seismic approach identified low density clay materials in the clay core, low density rockfill, and poor quality rock in the dam foundation.