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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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Vision

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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
- Representing the United States as an active member of the International Commission on Large Dams (ICOLD).

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CHARACTERIZATION OF GEOLOGIC FEATURES AFFECTING SEEPAGE THROUGH CARBONATE DAM FOUNDATIONS

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ABSTRACT

Physiography, lithology, stratigraphy and geologic structural influences all play a significant role in the behavior of carbonate bedrock underlying many dam foundations constructed in humid regions of the eastern and central United States. Understanding these influences is essential to the evaluation and successful mitigation of seepage through carbonate dam foundations, many of which were conceived, investigated and constructed in the middle of the last century. Integration of essential geologic contextual information with historic records and well planned and carefully executed non-intrusive and intrusive investigations will yield data essential for solving complex carbonate rock problems. However, careful and continuous compilation and analysis by experienced geologists and engineers is required if data from investigations are to be converted into sound science and engineering solutions. Recently completed and ongoing seepage remediation projects for dams founded on carbonate bedrock provide the back drop and frame of reference for a review of commonly deployed investigative techniques.

INTRODUCTION

Geologic features often control seepage development through carbonate dam foundations. Exploration and characterization of geologic features therefore becomes necessary when addressing seepage issues beneath dams founded on carbonate rock. Such exploration and characterization may be needed for a variety of purposes, including identifying seepage flowpaths, developing seepage models, evaluating remediation options, preparing designs, determining technical procedures and requirements for treatment options, estimating costs, and evaluating results of seepage reduction efforts.

The types of geologic information commonly required pertain to the nature and characteristics of unconsolidated materials, geologic structure, rock stratigraphy and quality, and discontinuities (size, orientation, attitude, spacing, and in-filling). Hydrogeologic information needs may include the distribution of potentiometric head and foundation permeability and locations of special features (faults, highly broken or weathered zones, buried valleys, and solution features) that may affect flow paths.

Knowledge of geologic features may influence several aspects of a seepage remediation or foundation rehabilitation project. In the case of grouting projects, knowledge of

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geologic features may influence the number of grout lines and their bearings; grout hole orientation, depth, and spacing; length of grout stages; grout mix design, and selection of grouting equipment and methods (e.g., upstage or downstage). On diaphragm wall projects, knowledge of geologic features may influence the depth and width of the wall, construction method (e.g., panel or secant pile), and selection of equipment to be used for wall construction.

Carbonate dam foundations pose special challenges for a variety of reasons. In comparison to siliclastic sedimentary strata, carbonate strata may exhibit peculiar to unique stratal patterns as a result of the capacity of carbonate sediments to be generated and accumulate in situ as build-ups, to be transported and deposited as clastic particles with a wide array of textures, and to erode subaerially, chiefly by dissolution (Handford and Loucks, 1993, p. 13). Carbonates have a fairly extensive distribution in the United States and frequently occupy valley bottoms in humid regions. Carbonate rocks are prone to dissolution, which can result in fracture enlargement and development of sinkholes, caves, and caverns. In comparison to non-carbonate rocks, carbonate rocks tend to be less homogeneous and more permeable and to have a wider range of permeability (Driscoll, 1986, p. 75).

THE ROLE OF GEOLOGY IN SEEPAGE DEVELOPMENT

Stratigraphy, structure, and physiography may profoundly affect or influence seepage development beneath dams founded on carbonate rocks. The experiences of the authors on several dam foundation grouting projects over the past decade provide examples of the role geology may play in seepage development.

<u>Stratigraphy</u>

As a result of changes in the depositional environment, diagenesis, erosion, and faulting, carbonate rocks may vary significantly in their relative solubility and may be interbedded with non-carbonate rocks. The presence of more soluble, less soluble, and relatively insoluble strata can profoundly affect seepage development. The role of stratigraphy in seepage development in carbonate rocks is evident from foundation grouting projects completed at Patoka Lake in southern Indiana, Mississinewa Dam in northern Indiana, and Wolf Creek Dam in Kentucky.

Figure 1. Sinkhole in spillway of Patoka Lake in Spring of 1996 (Photo courtesy of Stephen Hornbeck, USACE, Louisville District).

<u>Patoka Lake</u>: Following development of sinkholes in the spillway in 1996 (Figure 1), a grout

curtain was constructed in the left abutment ridge between the spillway and Patoka Dam to fill in a gap in the existing subsurface barrier of cut-off walls and grout curtains. The geologic literature (Gray, 1963) and exploratory core borings indicated the presence of alternating carbonate and non-carbonate bedrock layers. Pennsylvanian age sandstone of the Mansfield Formation capped the left abutment ridge and rested unconformably on Mississippian age rocks, which in descending order, consisted of the Glen Dean Limestone, the Hardinsburg Formation (sandstone and shale), and the Haney Limestone.

Figure 2. Entrance to Robert Hall Spring Cave in left abutment ridge of Patoka Dam.

The presence of the relatively less soluble Hardinsburg Formation favored the development of horizontal solutioning within the lowermost portion of the Glen Dean Limestone. The degree of solutioning is strikingly evident in the development of the Robert Hall Spring Cave beneath the left abutment ridge approximately 2,000 feet downstream from the grout curtain. Inspection of the cave indicated the main cave passage attains its greatest width in the lowermost portion of the Glen Dean Limestone, and the stream flowing through the cave has barely incised the underlying Hardinsburg Formation (Figure 2).

<u>Mississinewa Dam</u>: Sinkhole development at Mississinewa Dam in northern Indiana resulted in development of a remedial strategy that included, pre-grouting of the carbonate bedrock to permit construction of a cut-off wall.

Figure 3. Enhanced solutioning in the Liston Creek Limestone Member of the Wabash Formation at the Cliffs of the Seven Double Pillars along the Mississinewa River.

The eastern portion of the dam was founded on glacial till underlain by Silurian age bedrock consisting of the Liston Creek Limestone and the Mississinewa Shale Members of the Wabash Formation. Core borings and the pattern of grout takes and permeability indicated enhanced solutioning of the lower portion of the Liston Creek Limestone Member above its contact with the less soluble Mississinewa Shale Member.

Approximately two miles downstream of Mississinewa Dam, the enhanced solutioning is strikingly evident on the east side of the Mississinewa River in a scenic feature known as the “Cliffs of The Seven Double Pillars” (Figure 3).

<u>Wolf Creek Dam</u>: Wolf Creek Dam on the Cumberland River in south central Kentucky impounds Lake Cumberland, which is the largest reservoir east of the Mississippi and the ninth largest in the U.S (USACE, 2008). Muddy flows in the tailrace and development of sinkholes at the embankment toe in 1968 led to an emergency investigation and grouting program from 1968 to 1970, which is generally credited with saving the dam. To further control seepage, a concrete diaphragm wall was constructed through the embankment between 1975 and 1979. However, seepage remained a problem, and in advance of construction of a new cut-off wall, pre-grouting of the bedrock was performed from January 2007 through September 2008 and additional grouting is planned in preparation for construction of a second cutoff wall.

At Wolf Creek Dam, the abutments are capped by remnants of Mississippian limestone of the Fort Payne Formation resting on the Devonian age Chattanooga Shale, which unconformably overlies Ordovician age carbonate rocks belonging to the Cumberland, Leipers, and Catheys Formations (Figure 4).

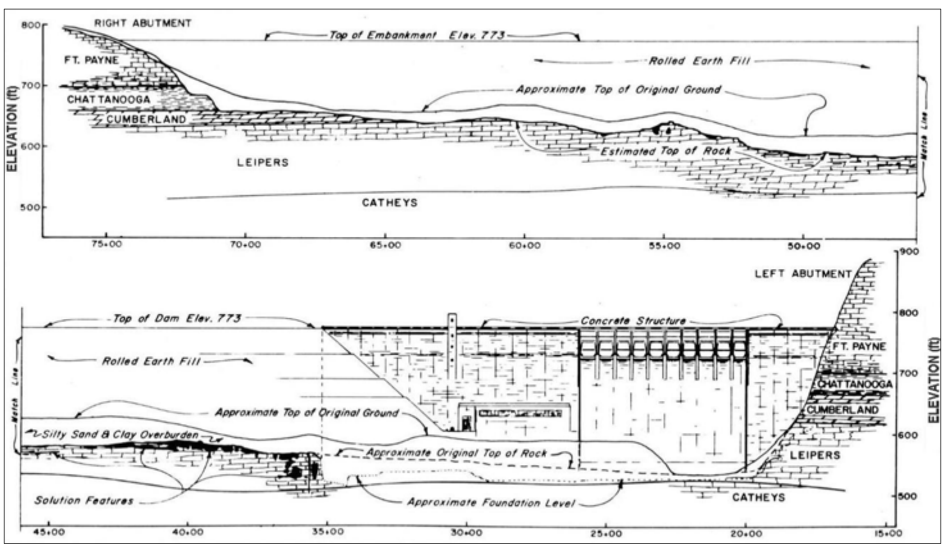

Figure 4. Upstream-looking geologic section of Wolf Creek Damsite (Kellberg and Simmons, 1977, p. 263).

Solution features are well exposed in outcrops of the Mississippian limestone above the Chattanooga Shale; however, very limited solutioning was evident in the carbonate rocks below the Chattanooga Shale, which was approximately 35 feet thick in the right abutment. In the valley, water pressure testing results and grout takes generally increased with distance beyond the subcrop of the Chattanooga Shale and solution features of significance are known to exist in the vicinity of the intersection of the earth embankment and concrete portion of the dam.

Structure

Structure refers to the spatial relationships of rocks and their discontinuities resulting from deformational processes such as folding, faulting, shearing, compression, and extension. Structural features such as folds, faults, and fractures may affect seepage development in carbonate rocks. The role of structure in seepage development in carbonate rocks is evident from the Patoka Lake, Wolf Creek Dam, and Clearwater Dam projects.

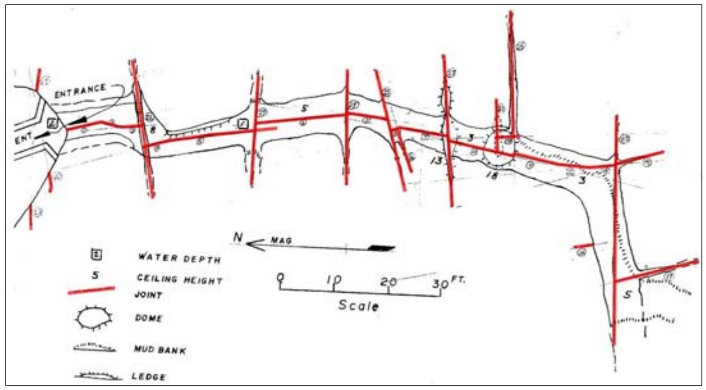

Figure 5. Robert Hall Spring Cave, Patoka Lake.

Patoka Lake: Examination of the Robert Hall Spring Cave illustrates the role of jointing in seepage development. In the map of the cave presented in Figure 5, the near vertical joints are highlighted in red. From the map, it is clear that the cave runs parallel to a north-south-trending joint set before turning nearly 90 degrees along the east-west-trending joint set. Changes in bearing and widening of the north-south-trending cave passage along the east-west-trending joint set are evident. The increased ceiling height at joint intersections indicates development of vertical shafts or domes as a result of enhanced solutioning at these points of weakness in the rock mass.

Wolf Creek Dam: Wolf Creek Dam is situated in the Eastern Highland Rim which has been dissected by the Cumberland River and its tributaries. The drainage pattern is very angular and appears to be controlled by jointing and very minor folding as the strata are nearly horizontal. The strata are cut by two major sets of near vertical joints—one trending N40°-76°E and the other trending N20°-75°W (Kellberg and Simmons, p. 264). Fractures and lineaments inferred from topographic mapping are shown in Figure 6.

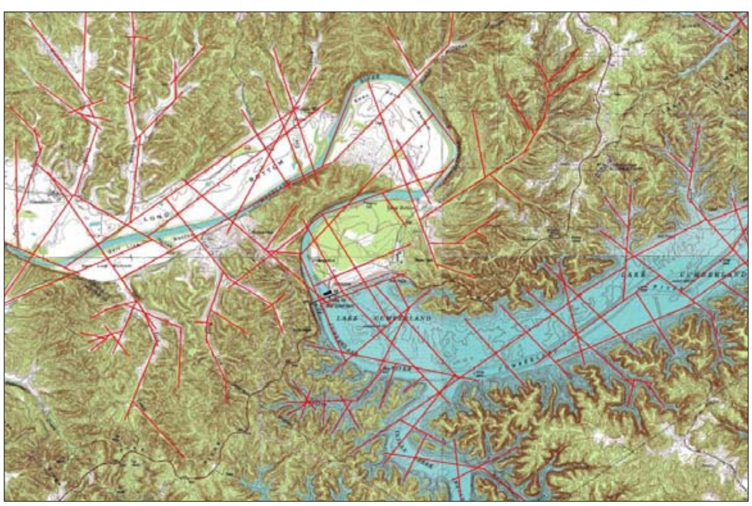
Figure 6. Map of fracture traces inferred from topography in the vicinity of Wolf Creek Dam.

Karst development in the vicinity of the dam is consistent with the pattern of jointing and appears to be controlled by these structural elements. The core trench was constructed in an existing northeast-trending, linear channel upstream of the axis of the dam. This channel is interconnected with northwest trending joints that comprise potentially significant seepage flow paths.

Clearwater Dam: Discovery of a sinkhole on the upstream face of Clearwater Dam in January of 2003 resulted in a sinkhole repair project involving injection of high- and low-mobility grout. Further rehabilitation of the dam is being performed in two phases consisting of an investigative drilling and grouting program followed by construction of a concrete cut-off wall the entire length of the embankment.

Figure 7 provides a rose diagram displaying a histogram analysis of the strikes of 19 vertical to subvertical joints measured using a Robertson Geologging televiewer in two boreholes in the vicinity of the sinkhole. Joint sets trending east-northeast, northwest, and northeast are evident. The northwest trending joints appear to be related to the eastern terminus of the Ellington Fault, and the east-northeast-trending set may be related to the Ouachita orogeny, which has been linked with similar trending sets recently mapped by the USGS in areas to the west and southwest of Clearwater Dam (R. Orndorff, USGS Personal Communication, 2008).

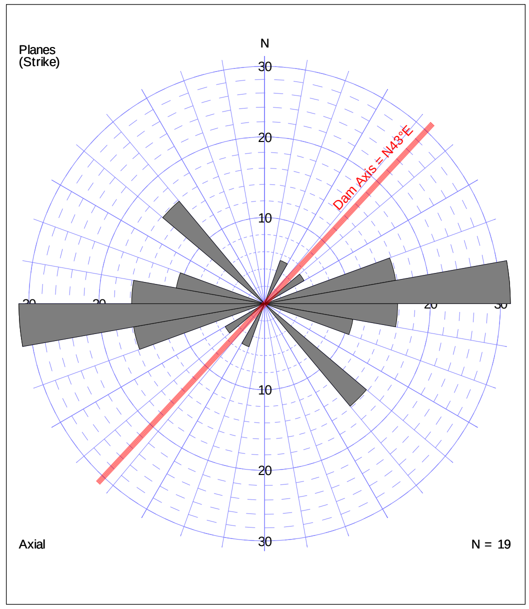

Figure 7. Rose diagram displaying histogram analysis of strikes measured on 19 vertical to subvertical joints at Clearwater Dam.

Physiography

Dams are situated in river valleys. In carbonate terrains, river valleys may be complex and include reaches that flow above the surface, below the surface, or both depending on stage. The forces that shaped the river valley may also influence seepage.

Wolf Creek Dam: Prior to impoundment by Wolf Creek Dam, the Cumberland River channel had incised the Ordovician limestone bedrock to approximately Elevation 530 at the left abutment. The top of rock profile along the upstream grout line completed in 2008 (Figure 8) reveals two terraces cut into the bedrock: one at approximately Elevation 645 (near Cumberland/Leipers contact) from Station 55+00 to 65+00 and another at approximately Elevation 585 from Station 47+00 to 51+00.

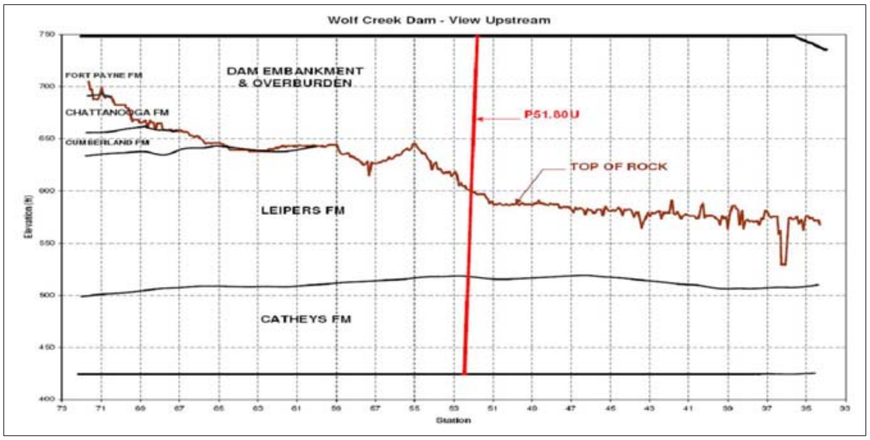

Figure 8. Profile along upstream line of grouting project completed in 2008 at Wolf Creek Dam.

Situated at the escarpment between the two terraces, a series of grout holes were the locations of the highest grout takes experienced in the pre-grouting project. Boring P51.80U and nearby boring P51.60U took more than 65,000 gallons of grout. The high takes at the escarpment between the old stream terraces indicate higher permeability in this zone. High takes adjacent to valley walls are not uncommon in flat-lying carbonates because of enhanced solutioning as a result of greater heads, and development of flow paths along vertical joints and bedding planes as a result of stress relief and erosional unloading. High takes were also observed in the cavernous zone between Station 33+60 and Station 36+00 beneath the youngest terrace at the western end of the grouting project completed in 2008.

<u>Clearwater Dam</u>: The northwest-trending and northeast-trending joint sets are consistent with the overall structural grain that exists throughout the state of Missouri (McCracken, 1966). The dam is situated southwest of the St. Francois Mountains and within the Ozark Plateau and is northwest of the seismically active portions of the Mississippi embayment, so the bedrock has experienced significant stress as a result of uplift and subsidence. Large solution-enhanced features that were identified in the dams core trench are most certainly related to regional tectonic patterns. Figure 9 depicts the solution features as they were shown on a historic drawing. One trends approximately N57°W and the other approximately N80°E. The January 2003 sinkhole appears to be associated with the latter set. These and related features may influence physiography, stream drainage patterns and the irregular valley development found in the carbonate rocks of the Ozark

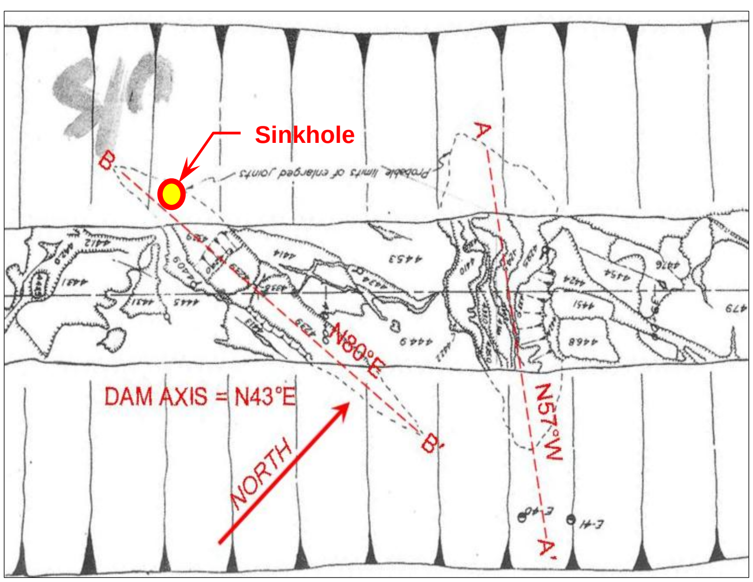

Figure 9. Clearwater Dam foundation drawing showing strikes of large solution features and location of January 2003 sinkhole.

Plateau by a headward growth mechanism through coalescence and collapse of sinks suggested by Harvey and others (1977, p. 8).

TOOLS FOR EXPLORING AND CHARACTERIZING GEOLOGIC FEATURES

Many tools are available for exploring and characterizing carbonate dam foundations. Desk top methods include review of construction documents, geologic literature, and foundation reports. Non-intrusive reconnaissance may include discontinuity surveys, flow path mapping, and geophysical surveys. More intrusive techniques include test borings and permeability testing.

Review of Construction Records, Photographs and Foundation Reports

Extremely valuable information is contained in owner archives and the records of investigation and construction for many dams developed in the United States. Despite the fact that many decades have passed since these dams were conceived, investigated, constructed and put into service during a boom of infrastructure development in the early to mid -20th century; very important records exist that were thoughtfully prepared by details-oriented practitioners. These records comprise a significant resource for guiding present day dam remediation strategies and include Foundation Completion Reports; Soils Laboratory Reports; Monitoring and Surveillance Records as well as a variety of photographs, drawings, plans, and correspondence.

At the Wolf Creek Dam, the core trench passes through and was constructed within a solution channel and cavernous section of Leipers limestone. The caves photographed and mapped during construction have linear aspects and tend to run parallel to the northwest-trending joints present at the dam site and in the local area.

The dramatic historic photograph in Figure 10 shows the size and orientation of discontinuities and solution features exposed and treated during dam construction. The photograph clearly depicts a challenging work environment but it also shows subsurface conditions with significant challenges to effective management of permeability in a complex carbonate host rock. .

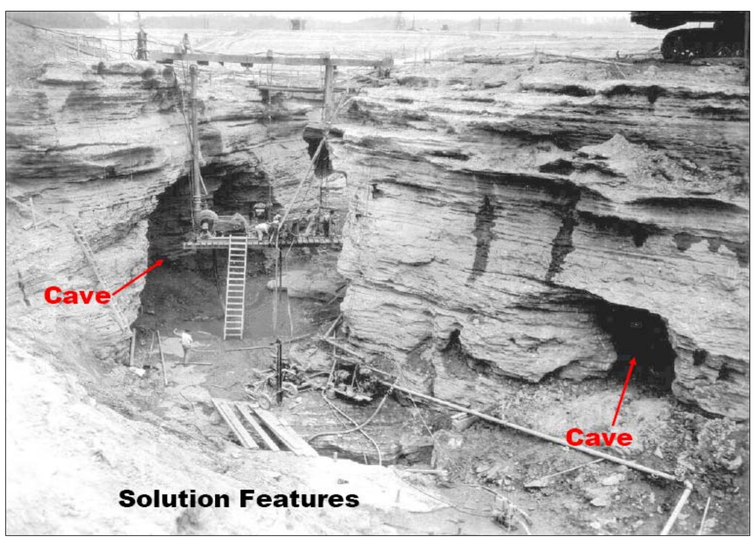

Figure 10. Caves exposed in core trench during construction of Wolf Creek Dam.

At Clearwater Dam, the current seepage remediation strategy is being guided by the findings of an ongoing exploratory program, as well as historic documents which include a number of very important documents prepared by the original site investigators. The project record contains contributions from Arthur Casagrande, who provided support from his office at Harvard University in the 1940's.

Among influential documents is a rendering (Figure 11) which depicts a deep-seated cavernous zone within the dolomite foundation bedrock. The depth of this feature and absence of an impermeable layer into which to tie the proposed seepage barrier means

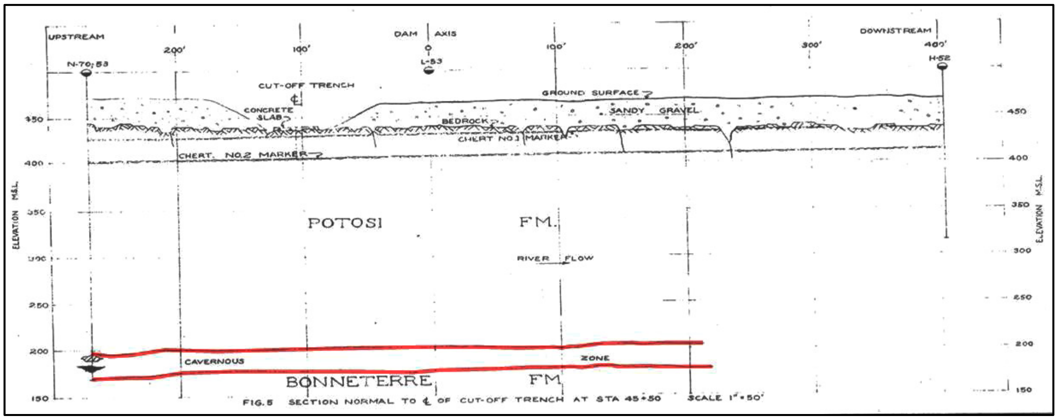

Figure 11. Cavernous Zone beneath Clearwater Dam (Source Foundation Report Cut-off Trench Section II Plate I-26, Sta. 45+50)

that the preferred solution will be a "hanging" cutoff in otherwise fairly permeable Upper Cambrian carbonate bedrock.

Review of Geologic Literature

Fundamental to evaluation of geologic conditions at nearly every location in the United States are published reports and mapping produced by government and research institutions. Typically costing as little a few dollars per publication these sources of basic information are among the most economically obtained compilations of geologic data to be found anywhere. Geologic literature may be obtained from the U.S. Geologic Survey (USGS), state geologic surveys, and the publications of numerous professional organizations (e.g., Geological Society of America, Association of Environmental and Engineering Geologists, American Association of Petroleum Geologists, etc).

Many internet portals exist for accessing geological literature and include commercial portals, such as the American Geological Institute's GeoRef Database and free portals such as the USGS National Geologic Map; USGS Geologic Names Lexicon ("GEOLEX"); USGS library catalog, and publications accessible via the websites of state geological surveys like the Tennessee Division of Geology Catalog of Publications.

Discontinuity Surveys

Figure 12. Fractured Cambrian Potosi dolomite exposed in right abutment of Clearwater Dam.

Clearwater Dam is situated south of the Ozark dome and northwest of the Mississippi embayment, so the bedrock has experienced significant stress as a result of uplift and subsidence in these areas. The Cambrian age Potosi Dolomite, which underlies the dam has experienced at least five episodes of major deformation, each a result of renewal of uplift in the Ozark area (McCracken, 1971). The bedrock is extremely fractured (Figure 12).

Due to the capacity of fracture systems to enhance fluid movement through bedrock and the propensity of many carbonate rocks to dissolve along paths of fluid movement, it is essential to understand the nature of bedrock discontinuities when evaluating dam foundations.

Discontinuities can include fractures, joints, faults, folds and foliation. However, the most common features are joints and fractures. Fracture and joint orientation, spacing, continuity, persistence and aperture are all attributes of value in assessing the influence that these geologic structures have on seepage pathways. Joints confined to individual beds may be classified as non-through-going, while joints extending across bedding planes into surrounding beds may be classified as through-going. Measurement of joint aperture includes all effects of dissolution along the joint planes such as displayed in Figure 13.

Figure 13. Dissolution opening in exposure of Catheys Formation, Center Hill Dam

Flow Path Mapping

Figure 14. Green dye introduced into a spillway sinkhole showed up at Robert Hall Spring Cave at Patoka Lake.

A common technique for tracing seepage pathways and fluid migration is the introduction of dyes or other tracer compounds into a suspected upstream influent location and monitoring of a suspected downstream effluent location. This technique was employed at Patoka Dam and produced the desired flow path delineation (Figure 14). Much has been written about tracer testing which is beyond the scope of this discussion but Ground-Water Monitoring in Karst Terranes Recommended Protocols & Implicit Assumptions (Digital Version Courtesy of The Karst Waters Institute (*www.karstwaters.org*) by James Quinlan (1989) offers useful considerations.

A relatively recent approach for seepage flow path identification/modeling has been developed by *Willowstick Technologies, LLC* (Willowstick) for use in evaluating conditions within earthen embankments of dams and levees. A cornerstone of Willowstick technology is a specialized geophysical technique called *AquaTrackTM*..

According to Willowstick (2007), "AquaTrack is a geophysical technique that uses Controlled Source – Audio Frequency Domain Magnetics (CS-AFDM), which uses a low voltage, low current audio frequency electrical signal to energize the groundwater or seepage area of interest." Electrodes are typically placed upstream and downstream of an earthen embankment to energize the groundwater or seepage area,. The upstream electrode is placed in the reservoir water body distal from the face of the embankment. The downstream electrode is placed in strategic locations (seeps, observation wells, or other downstream locations) to facilitate contact with seepage flowing through the embankment. Following the preferential pathways of least resistance, the electrical current concentrates in highly saturated zones through, beneath, and/or around the earthen embankment and creates a measureable magnetic field that can be identified and surveyed from the surface of the ground using sensitive magnetic sensors. The measured magnetic data are then processed, contoured, modeled and interpreted in conjunction with existing hydrogeologic information to provide potential flow path identification.

Techniques developed by Willowstick have found application at a number of dams founded on carbonate bedrock including high priority structures like Clearwater Dam, Wolf Creek Dam, and Center Hill Dam. At these locations, Willowstick findings are being integrated with historic and current seepage data.

Geophysics

After the detection of a sinkhole in January 2003 following the Pool of Record in May 2002 at Clearwater Dam, a number of expedited investigations were undertaken by the USACE, Little Rock District to assess subsurface conditions and to determine appropriate remedial actions. The non-intrusive portion of the investigations included three types of seismic geophysics: seismic reflection; surface wave imaging using multi-channel analysis of surface waves (MASW); and cross-hole seismic used to develop seismic velocity profiles of unconsolidated materials and shallow bedrock. Other geophysical techniques including microgravity and electrical resistivity methods are also applicable in karst settings.

Seismic Reflection is a traditional geophysical technique that was used to investigate residual alluvium and the underlying bedrock as much a several hundred feet below the bedrock surface. This method evaluates the reflection travel times and amplitudes of reflected seismic energy (P or S wave) from acoustic pulses generated at predetermined source locations along the length of the reflection seismic profile. The recorded travel time–amplitude information is used to generate a reflection seismic profile and can be transformed into a velocity–structure profile. At Clearwater Dam the surface wave data were generated using a 25 to 250 hertz IVI "minivib" source (Figure 15) and collected on a 240-channel Geometrics StrataView seismograph (recording two 120-channel parallel lines) using 40-hertz geophones and a 4-foot receiver station spacing. The seismic reflection survey identified two areas where apparent subsidence/erosion has occurred along the upstream edge of the clay core.

Figure 15. Mini-Vib seismic source for geophysical investigations Clearwater Dam (Source: Miller et al, SAGEEP 2004)

MASW is a relatively new seismic method that utilizes standard seismic recording instrumentation to record the vertical distribution of shear wave based upon the dispersion of surface waves (Rayleigh Waves). MASW was used to interrogate dam materials relative to their shear wave velocities as a measure of material stiffness. At

Clearwater Dam the surface wave data were generated using an accelerated weight drop and collected on a 240-channel Geometrics StrataView seismograph (recording two 120-channel parallel lines) using 4.5-hertz geophones and a 2-foot receiver station spacing. Surface wave profiling revealed relatively lower shear wave velocities in the vicinity of the sinkhole and suggested the existence of a second sinkhole northeast of the sinkhole that formed in January 2003.

Cross-Hole Seismic typically uses high-frequency acoustic pulses generated at predetermined source locations in a source borehole. The amplitude and arrival time of direct arrivals (and others) is recorded at predetermined receiver locations in the receiver borehole. The recorded travel time–amplitude data are statistically analyzed and used to generate a velocity–attenuation cross-sectional model of the area between the source and receiver boreholes. If external constraints are available, the velocity–attenuation profile can be transformed into a geologic model. At Clearwater Dam the cross-hole study provided clear evidence of voids and fissures within bedrock that appeared to be vertical chimney-like structures, traceable into the residual alluvium and pervious shell material.

Core Borings

Core borings have, since the invention of the rotary core boring drill rig, been an essential intrusive element in probing and investigation of subsurface conditions for all types of civil infrastructure. Core drilling remains essential to evaluating foundation conditions for a wide variety of purposes, including identifying seepage flowpaths, developing seepage models, evaluating remediation options, preparing designs, determining technical procedures and requirements for treatment options, estimating costs, and evaluating results of seepage reduction efforts.

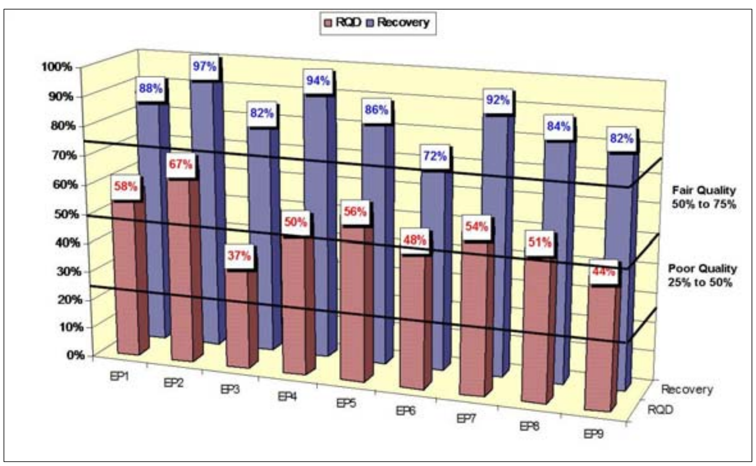

Figure 16. Recovery and RQD data for 9 exploratory core borings at Clearwater Dam.

The inherent value of well placed borings in a thoughtfully constructed core boring program cannot be understated, and, in terms of revealing the make-up and composition of subsurface materials and subsurface conditions of all types, core borings are unrivaled. This is especially true in areas underlain by carbonate rocks where lithologic variations and geologic discontinuities often combine forces in development of karst topography and endless variations of secondary bedrock permeability

Core borings allow us to directly sample, directly observe and closely examine subsurface soil and bedrock for the purpose of gaining first hand understanding of conditions relevant to the construction, operation, remediation, and rehabilitation of dams underlain by carbonate rock. Core borings provide the opportunity for direct physical examination and logging of rock quality measures such as Recovery and RQD (Figure 16) by experienced geologists, geotechnical engineers and karst specialists.

Core borings provide the raw materials essential to petrographic analyses (Figure 17) and materials testing programs that further enhance our understanding of the behavior of earth materials in the constructed environment. The minimum standard for scientific and forensic evaluation of dam foundation conditions is to employ triple-tube coring systems where the rock core is preserved intact for geologist examination, rather than banged from the bottom of a double-tube system by the driller's helper.

Figure 17. Petrographic thin section of Potosi dolomite, Clearwater Dam

One of the most vigorously debated topics among practitioners who have had the good fortune to have been exposed to both core drilling as well as advanced borehole imaging techniques and other down-hole (geophysical) methods, is the question of which method is preferable. In the context of scientific investigation it is clear that both types of investigation have their place in characterization of dam foundations, acknowledging that each type of investigation technique possesses positive and negative attributes.

Borehole Imaging

Commonly available borehole imaging systems range from fairly simple forward looking and pan and tilt down-hole camera and recording systems to more sophisticated optical (OTV) and acoustic televiewer (ATV) systems available from a number of manufacturers. Although both types are still commonly used to evaluate subsurface foundation conditions, OTV/ATV systems represent a quantum leap forward because of their ability to produce continuous and oriented 360-degree high quality digital images under a wide variety of borehole conditions (Figure 18). Such systems have been deployed on recent carbonate dam foundation remediation projects including Clearwater, Wolf Creek and Center Hill Dams.

According to Williams and Johnson (2004), the first ATV was developed by the petroleum industry in the late 1960s and although used by some researchers earlier, widespread application of acoustic imaging studies did not occur until the mid- to late 1990s with the development of ATV tools directly compatible with common slim hole geophysical logging systems. The first OTV was developed as a stand-alone system in 1987.

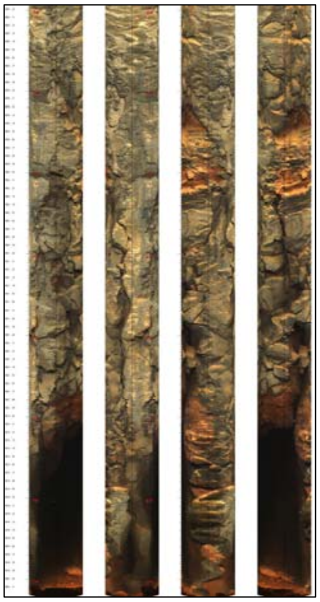

Figure 18. Oriented borehole images Clearwater Dam Boring BP53 showing 3 foot conduit.

ATV imaging systems use an ultrasonic pulse-echo configuration in which transit time and amplitude of the reflected acoustic signal are recorded as photographic-like images collected along a spiral trajectory along the borehole wall. Images can be collected in water- or light mud-filled intervals of boreholes and borehole enlargements related to structures such as fractures, foliation, and bedding planes scatter energy from the acoustic beam, reduce the signal amplitude, and produce recognizable features on the images.

OTV imaging systems use a ring of lights to illuminate the borehole, a camera, and a conical or hyperbolic reflector housed in a transparent cylindrical window. The camera measures the intensity of the color spectrum in red, green, and blue, and the reflector focuses a 360-degree slice of the borehole wall in the camera's lens. Lithology and geologic structures such as fractures, fracture infillings, foliation, and bedding planes are viewed directly on the OTV images which can be collected in air- or clear-water-filled intervals of boreholes.

Orientation of acoustic and optical televiewers is accomplished by a three-axis fluxgate magnetometer and three accelerometers, which provide an oriented borehole-wall image and true three-dimensional location of the measurement. Processing of images includes rasterization of the spirally-distributed log data onto a rectangular grid, determination of the trajectory of the borehole-axis and identification and labeling of significant geologic features along with their orientation and depth on the borehole-axis.

<u>Drilling Water Loss and Water Pressure Testing</u>

Observations of drilling water circulation, loss and relative loss during exploratory and production drilling can reveal important information about seepage pathways and flow conduit development in carbonate rock. They can also reveal how bedrock treatment sequences are affecting change in permeability conditions (Figure 19).

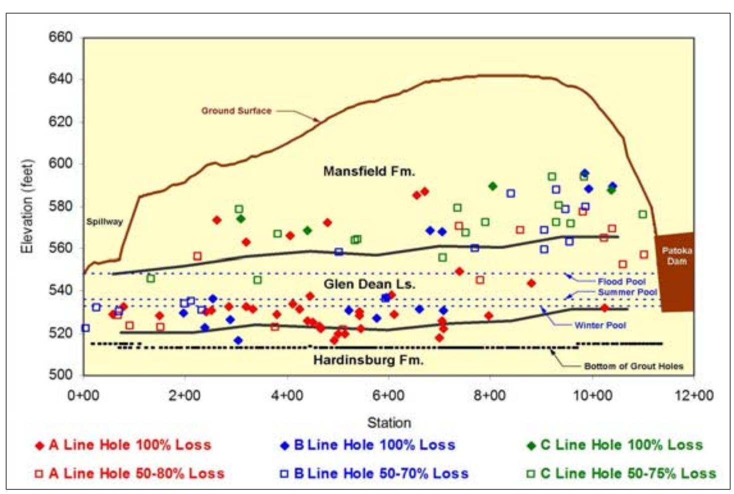

Figure 19. Downstream-looking cross section of the left abutment of Patoka Dam showing drill water losses.

Preferential solutioning of the lowermost portion of the Glen Dean Limestone is also evident in the pattern of water losses observed during drilling at Patoka Lake. 102 water losses were recorded in the 469 holes drilled on the main triple-line segment of the grout curtain. A concentration of water losses is evident in the lower portion of the Glen Dean Limestone, especially in the zone below normal pool level, suggesting higher permeability as a result of enhanced solutioning of this zone (Figure 4). The water loss data also reflect the effect of grouting as the frequency, magnitude, and depth of water losses decreased as work progressed from the downstream A Line (51 losses), to the upstream B Line (31 losses), and the intermediate C Line (20 losses).

Water pressure testing provides a direct method of assessing bedrock permeability and a means for comparing carbonate dam foundation strata to each other and other locations within the same project or to different projects. Water pressure testing completed in exploratory borings revealed that the permeability of the Potosi dolomite ranges from about 20 to 200 Lugeon and does show modest variation with respect to elevation.

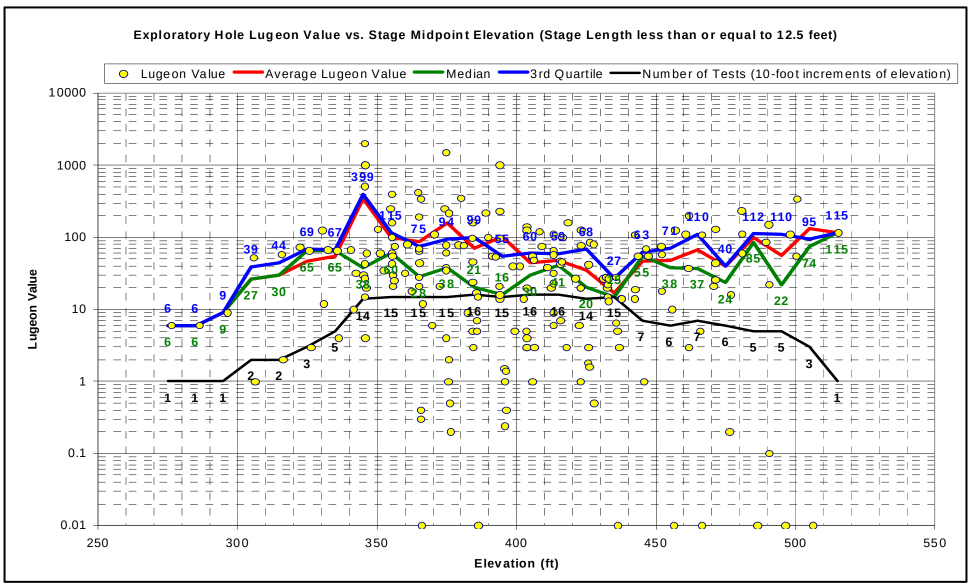

Figure 20. Exploratory Boring Lugeon Value versus Stage Midpoint Elevation, Potosi Dolomite, Clearwater Dam

THE CASE FOR CONTINUOUS INTEGRATION OF GEOLOGIC DATA

Dam foundations established on carbonate bedrock present technically challenging conditions for which complex engineered solutions are often prescribed and for which competently conducted scientific investigations are clearly warranted. However, the many means and methods of data collection described in this paper are value-less without attentive compilation and careful integration.

Formulating sound science solutions to the complex problems found in today's most significant dam remediation projects requires that experienced geologists and engineers ply their craft with the diligence, precision, accuracy and attention to detail. These are traits that are as admired today as they were in the middle of the last century when many of our current dam remediation projects were conceived, investigated, and constructed.

Technological advancements permit us to store, catalog, retrieve, analyze and evaluate information in ways our predecessors could only have imagined. However, these same advancements may also rob us of reflection opportunities which in the past allowed these same predecessors to devise visionary solutions to complex problems. The legacy we leave behind is the well done work that we do. This fact alone should sufficiently motivate us to conduct fully integrated investigations with open curiosity and cataloging discipline.

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