ICOLD Symposium on Sustainable Development of Dams and River Basins, 24th - 27th February, 2021, New Delhi

SUBSURFACE INVESTIGATION OF A MAJOR DAM FOUNDED IN KARSTIC TERRAIN

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ABSTRACT

This paper describes the intrusive and non-intrusive exploration methods used during the subsurface investigation of a major dam in southern United States. The Dam is located on a karstic foundation. The dam leaks a significant volume of water. Numerous sinkholes have formed in the upstream side of the dam in the last several decades, which were repaired locally. The Dam has been assigned a Dam Safety Action Classification (DSAC)-II Potentially Unsafe rating. The investigation was performed in support of the Dam Safety Modification Study (DSMS) conducted for the Dam. The paper presents how multiple investigation techniques were used to identify anomalies, corroborate previous findings, validate and calibrate information and develop a 3D geological model of the site. The field investigation included surface geophysics, downhole geophysics, soil borings, test pits, piezometers, dye tracing study, and installation of an extensive automated monitoring system. The geophysical study for the project included techniques such as microgravity, electrical resistivity imaging survey, and MASW. The 3D geological model of the site incorporates historical and recent site information. The model is a practical tool to visualize data, identify potential flow paths and help develop remedial measures.

1. INTRODUCTION

Subsurface investigations of existing dams are typically hindered by the dam itself which limits readily access to its foundation, massive grading that occurred during construction and lack of historical site data. This paper describes a successful investigation program of a dam located in a karstic foundation in the southern United States. The investigation program consisted of multiple intrusive and non-intrusive investigation methods that together provided very reliable and verifiable information of the embankment and foundation conditions of the dam.

The dam was constructed from 1963 to 1969. The total length of the dam is 9,760 meters and consists of a 665 meter long and 77.4 meter high concrete gravity section, which is flanked by 2,591 meters of earth embankment in the east and 6,504 meters of earth embankment in the west.

The concrete gravity section consists of a 292-meter ogee weir spillway. The concrete dam has non-overflow transition sections that are 28 meters long on both sides of the spillway. A power intake section that is 68 meters long is adjacent to both of the transition sections. The remainder of the concrete dam consists of a 91 meters non-overflow section between the power intake monoliths and the earth embankment on either bank. The maximum height of the concrete section is approximately 77 meters and the maximum height of the embankments is about 37 meters.

The main geologic unit of the dam is Georgetown Limestone, which exhibits soluble nature and includes fractures and cavities. Numerous sinkholes have been developed in the upstream of the dam in the last several decades. The eastern embankment of the dam also has potential for filter incompatibility. A technical advisory panel identified six major potential failure modes of the dam, which are related to foundation (solution cavities) and embankment (filter incompatibility) conditions. A comprehensive geotechnical and geophysical investigation program was performed by AECOM (legacy URS) to explore these conditions and to provide baseline data for the development of remedial alternatives. The investigation consisted of surface geophysical survey, exploratory borings, piezometers and observation wells, laboratory testing, downhole geophysics, sediment basin, and test pits. This integrated investigation program was developed based on an in-depth review of historical documents on dam design, construction, and performance, and the targeted geophysical survey and exploratory borings provided valuable insights to the subsurface conditions at the dam. This paper discusses the approach and key findings with examples for the western embankment where excessive seepage in karstic geologic environment is a concern.

2. REGIONAL AND SITE GEOLOGY

The dam and surrounding area are within the Maverick Basin, a depositional basin that is part of the Ouachita thrust belt system. The Ouachita thrust belt is a northeast-southwest-trending structural belt that extends from the state of Arkansas to the state of Chihuahua in Mexico. The Ouachita thrust belt was formed from the late Paleozoic collision of the North and South American continental plates. This tectonic belt has resulted in a series of deep basins and exposed tectonically deformed and folded highlands (Hickman et. al., 2009). The Maverick Basin spans an area of approximately 200 square miles (mi^2) (518 square kilometers [km^2]) in southwest Texas and Mexico. The rocks of the Maverick Basin are predominantly Cretaceous-age marine deposits ranging from argillaceous mudstone to limestone. Figure 1 shows a geologic map of the western embankment with sinkholes.

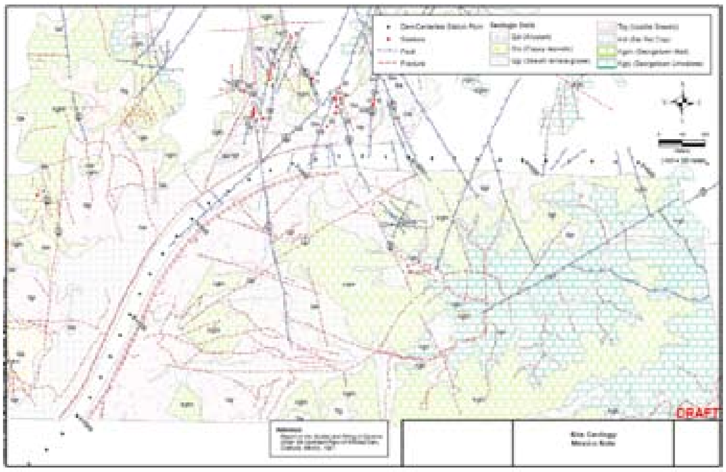

Figure 1 : Surface Geologic Map for the Western Embankment

3. KEY ASPECTS OF THE DAM DESIGN, CONSTRUCTION, AND PERFORMANCE OF THE WESTERN EMBANKMENT

A review of historical design, construction, performance, and maintenance documents reveal the following key aspects of the Dam:

3.1 Solution Cavities and Foundation Treatment on Western Embankment

Several large cavities were encountered during construction of the Western Embankment. These large cavities were encountered at Stations 5+580, 5+760, 6+180, 6+350, 6+360, 6+460, and 6+495. Figure 2 shows photographs of few cavities from construction photographs. Foundation treatments during construction included concrete infilling of cavities, dental concrete, and a grout curtain.

Historical foundation maps shows foundation treatment areas between Sta. 5+520 and Sta. 8+100. The large cavities that were infilled with concrete were generally oblique to the dam alignment. A total of 13 concrete infilling areas are present between Sta. 5+520 and Sta. 8+100. A single isolated concrete infilling area is also present outside of this zone, at Sta. 8+700. A dental concrete zone is shown within the clay core footprint between Sta. 5+520 and Sta. 6+725.

3.2 Seepage and Sinkholes in the Western Embankment and Reservoir

The impoundment of water in the reservoir began in 1968. Extensive seepage has been reported downstream of the western side of the dam since initial impoundment. A number of sinkholes have been formed in 1990s on the upstream of the western embankment. Most of the seepage is measured in two general areas: the Carmina and the Aroyo Jaboncillos basins. Seepage is measured at 35 monitoring locations. The Owner keeps records of seepage measurements and plots of seepage quantity with reservoir elevations.

On October 1993, sand was observed in the seepage waters in the Carmina Springs. A year after this observation at Carmina (October 1993-sand in seepage), the reservoir pool had receded to near elevation 328 meter. The pool had only been this low once since initial filling. In October 1994, with the pool at this approximate low level, a sinkhole was observed in the reservoir area on the western side. This feature was observed approximately 250 meters upstream of the dam toe at dam Station 7+100. Ten more sinkholes were observed in the same general area over the next three months. Two more sinkholes were then observed in June 1996 and an additional five in 1997. Most of these sinkholes were located between dam stations 6+500 and 7+200, and none of the reported sinkholes was closer than 200 meters from upstream toe of the dam. No new sinkholes formed between 2002 and 2006, a period of continuous monitoring.

Figure 2 : Photographs of Sinkholes From construction (clockwise from top-left: Station 5+580, 6+350, 6+360, and 6+495)

Based on the final report of the Technical Review Board convened to assess the dam, a possible explanation of these sinkhole formations is summarized as following:

The dam owner started a systematic backfilling of sinkholes program in 1995. The sinkholes were filled with granular materials consisting of larger rocks in the bottom, followed by cobbles, then gravel, and finally sand. Initially, the sinkholes were capped by concrete. Cracking and settlement displaced the concrete caps, which were subsequently replaced by mounds of granular materials which would move downward in the sinkholes, if further subsidence occurred.

3.3 Grouting Programs in the Western Embankment – 1995 (Centerline) and 1998 (Upstream)

In response to numerous sinkhole formations northwest of the dam, the Owner of the dam completed a detailed study of the western embankment that included surface geophysics, borehole geophysics, and installation of piezometers. Piezometers were installed in three lines perpendicular to the centerline of the dam.

After the 1995 study, the centerline of the dam was re-grouted between Sta. 6+850 and Sta. 7+450 (later in 1995). Also, a grouting program was implemented upstream along six segments of the dam within Sta. 6+850 and Sta. 7+450 in 1998.

The 1995 grouting program essentially consisted of re-grouting the curtain along the dam axis. The embankment in this re-grouting section is founded on Georgetown Marl. The intent of the grouting was to intercept potential seepage pathways and thus minimize the potential for internal erosion of foundation and embankment materials within the dam footprint. However, no change in downstream seepage was observed after the 1995 and 1998 grouting programs between Sta. 6+850 and Sta. 7+450.

4. INTEGRATED GEOPHYSICAL, DYE TESTING, GEOLOGICAL, LABORATORY TESTING, AND INSTRUMENTATION PROGRAM

An integrated investigation program was implemented at the dam to evaluate the following embankment and foundation conditions:

- Characterize the embankment materials in core and shell zones to evaluate the filter compatibility between core and shell materials
- Evaluate foundation conditions in the Western Embankment that might contribute to sinkholes on upstream and excessive seepage on downstream

This integrated investigation program consisted of the following tasks:

1. Performing a surface geophysical program consisting of microgravity, electrical resistivity imaging survey, and multichannel analysis of surface wave survey (MASW) along 11 lines with a total length of 6,875 meters.
2. Performing 14 borings in the eastern embankment and 61 borings in the western embankment. The distribution of borings is presented in Table 1:

Table 1 : Summary of Borings

Embankment	No. of Borings	Depth Range
Eastern Embankment	11 (Crest) 3 (Downstream Toe)	20 feet to 141 feet (Crest) 13 feet to 22 feet (Downstream Toe)
Western Embankment	16 (Crest) 4 (Downstream Slope) 35 (Downstream Toe) 6 (Upstream Toe)	77 feet to 163 feet (Crest) 98 feet to 122 feet (Downstream Slope) 10 feet to 103 feet (Downstream Toe) 100 feet to 155 feet (Upstream Toe)

3. Performing downhole geophysical survey at 49 exploratory boring locations. Downhole geophysical methods included gamma, resistivity – fluid column and short normal, spontaneous potential, caliper, acoustic or optical borehole televiewer.
4. Installing a series of instrumentation through the embankment and downstream locations. The instrumentation program included a total of 73 wells and piezometers.
5. Installing three settling basins to evaluate sediment characteristics from seepage exiting the downstream seepage areas known as Spring V-4, MG-13, and MF-13.
6. Performing 38 test pits in a potential borrow area downstream of the dam.

5. SUMMARY OF FINDINGS FROM SURFACE GEOPHYSICAL SURVEY

Based on review of different surface geophysical methods that are common in karstic geologic environments, microgravity, electrical resistivity imaging, and multi-channel analysis of surface waves were selected as the appropriate geophysical methods for the dam. Zonge, International provided the following descriptions of the surface geophysical methods in context of their use in identifying karst geologic features at the dam (Zonge, 2015).

The Microgravity geophysical survey method responds to changes in the gravitational field generated by differences in density of subsurface materials. These changes could be caused by the relief of the bedrock surfaces, intrusive bodies of materials with different mass or the density contrast between different geologic units. Voids in rock or soil will have a mass deficiency compared to the center of the mass deficiency, size of the target, and survey parameters.

The Electrical Resistivity Imaging (ERI) method is capable of identifying variations in subsurface geologic features where contrasts are present. Changes in the electrical properties of the subsurface are non-unique indicators of geologic conditions (Dahlin, 1996).

Variations in subsurface moisture content, porosity, permeability, and soil or rock type (i.e. lithology) affect electrical resistivity measurements. Cultural features (man-made features such as fences, power lines, pipelines, and buried debris) can also affect resistivity measurements. Depth of investigation for the ERI method is a complex function involving receiver array length and the electrical properties of the subsurface materials (Oldenburg and Li, 1999).

For a karst investigation, large air-filled voids would be characterized by extremely high resistivity values (as air is almost infinitely resistive). Fluid-filled voids, saturated sediments, or dissolution features would be characterized by anomalously low resistivity values if within a limestone bedrock, given that voids are most likely to be clay-or water-filled.

Limestone bedrock is expected to be more resistive than clays or clay- or fluid-filled dissolution features. Lower resistivity zones are interpreted to be fine grained alluvial silts and clay. These are indicative of conductive clay rich soils and may represent in-filled dissolution features. They might also result from sediment-filled erosional features.

Multi-Channel Analysis of Surface Waves (MASW) method responds to contrasts in the physical properties of soils, and to a lesser extent, rock. The method focuses on the dispersive characteristics of Rayleigh waves as they propagate through a layered medium. In a homogeneous material, there is no dispersion. The variations are non-unique indicators of geologic conditions (Park and Shawver, 2009).

Surface wave techniques are non-invasive and non-destructive, with all testing occurring at elastic strain levels. Depth of investigation for all seismic methods is a complex function involving receiver array length, the velocity distribution of the subsurface materials, and the source type and offset distance.

Limestone bedrock is expected to have a significant higher seismic velocity than clays or overburden sediments. Dissolution features may appear as low-velocity zones, if air-filled or filled with unconsolidated sediments.

The MASW method is a low-resolution method with poor ability to image small, isolated targets. MASW anomalies are distorted representations of subsurface features and have to be confirmed with more direct measurements. Lower velocity zones are interpreted to be fine-grained alluvial silts and clay.

Four geophysical survey lines were selected in upstream of the western embankment to evaluate the conditions in the area near known sinkholes. Three parallel lines along the downstream toe, dam crest, and downstream toe were conducted to evaluate the anomalous conditions across the dam. Three additional lines were surveyed in downstream of the dam near known seepage exit locations MG-13, MF-13, La Curva, and V-4. Structural geologic features such as faults and joints are also mapped across these surface geophysical study lines.

Geophysical anomalies were evaluated on the basis of their response, size, or corroboration between methods and were ranked from 1 through 4. Rank 1 anomalies represent those that were interpreted as being most critical for further evaluation. A total of 82 geophysical anomalies were identified from the processed geophysical data. These geophysical anomalies in many cases matched well with surface geologic features such as faults and mapped channels. Figure 3 shows a plan view of the western embankment with geologic mapping, surface geophysical survey lines and findings (Rank 1 through 4 anomalies), known sinkholes, and known seepage exit locations.

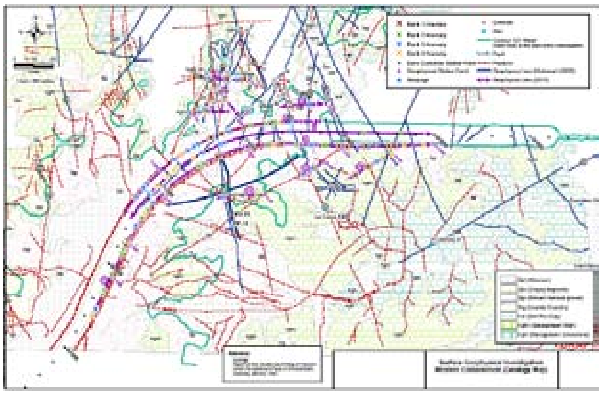

Figure 3 : Geologic Map with Surface Geophysical Survey Lines and Anomalies

6. SUMMARY OF FINDINGS FROM DYE TRACER STUDY

A dye tracer study was conducted to assess potential seepage paths through the karstic in the dam western embankment foundation. The dye tracer study was performed by Ewers Water Consultants, Inc. (EWC) with logistical support from AECOM in January 2015. Dye tracer was injected through four upstream points and monitored at 21 downstream locations. 12 existing piezometer/observation wells were also used as monitoring locations. Figure 4 shows a summary of dye tracer study locations.

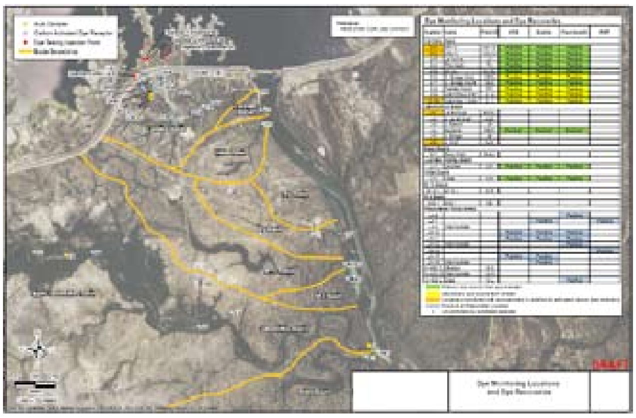

Figure 4 : Summary of Dye Tracer Study

The injected dyes were detected at all monitoring locations in Carmina Basin (C-1 through C-10), Loudres Basin (L-1), and Hilda Basin (H-1). Dye was not detected at monitoring locations in Jaboncillos Basin (J-1 through J-6), Buey Basin (B-1), M-15 Basin (M-15-1), and M-5 Basin (M-5-1).

From the collected data, the following observations can be summarized:

- Lack of connectivity between the dye tracer injection point locations and the Jaboncillos Basin;

- Clear connectivity between the injection points and the Carmina Basin;
- No clear preferential path was identified between the injection points and seeps and spring areas; and
- The broad detections of the dye at the downstream locations suggest interspersing of subsurface flow through the dam foundation.

7. SUMMARY OF FINDINGS FROM EXPLORATORY BORINGS AND DOWNHOLE GEOPHYSICAL SURVEY

The exploratory boring program consisting of 14 borings for the eastern embankment and 75 borings for the western embankment. Sonic drilling technique was used in embankment and through Alluvium, Del Rio Clay, and Georgetown Marl. Rock coring was performed in Georgetown Limestone. Total depths of 48 upstream and downstream borings ranged between 10 and 155 feet. Total depths of 27 crest borings ranged between 20 and 163 feet. Water pressure tests were also performed in Georgetown Limestone layers. Figure 5 shows a boring location map for the western embankment.

The locations of these exploratory borings were determined based on a review of historical documents on design, construction, and performance of the dam, surface geophysical survey performed as part of this study, and a historical detailed surface geology map of the site. The rationale for selecting boring locations in the western embankment included:

- Near known sinkhole locations
- Selected anomalies identified by surface geophysical surveys
- At mapped geologic features such as mapped faults and fractures
- Near known seepage exit locations
- Cavities identified during construction and known foundation treatment areas such as near V-4 seepage area
- Surface topography and geologic mapping indicating surface depressions or historic channels
- Near potential seepage path identified in historical and recent dye tracer study
- At selected locations through recently completed grouting in upstream toe

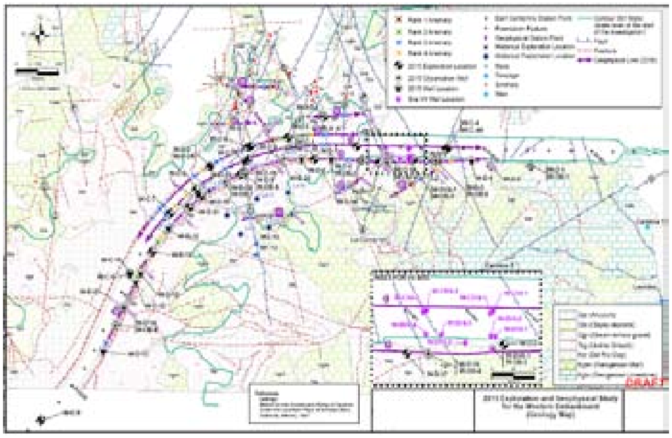

Figure 5 : Boring Location Map for the Western Embankment

Considering the potential scatter in size and location of solution cavities that exist in karstic geologic environment and the difficulty in targeting these with small diameter exploratory borings, the angle and direction of borings were adjusted based on close evaluation of geologic maps, topography and geophysical studies.

Cavities were documented in 23 of the 50 borings that were cored through the Georgetown Limestone adjacent to the western embankment. These cavities were logged where a gap exists in the limestone and the drill rods dropped during drilling (indicating the presence of a void) or where clay infill was observed. Most of the cavities were partially filled with clay, silt, and/or sand. In all of these instances, at least 50 percent water circulation was lost during drilling and usually 100 percent water loss was observed. The cavities ranged from 0.2 to 46 feet in length in the direction of drilling. Of the 35 cavities, 13 are less than 1 foot long. Water circulation was lost at all of these locations, indicating that water is able to move freely throughout the formation. Fourteen cavities were encountered that are greater than 1 foot and less than 10 feet long. Seven cavities encountered were greater than 10 feet long.

Downhole geophysical surveys were performed using Robertson Geologging (RG) Dual Induction (DUIN), 3-Arm Mechanical Caliper (CAL), Fluid Temperature/Conductivity (FTC), and ELOG probes to collect long and short electrical conductivity, long and short normal resistivity, single-point resistance, spontaneous potential, borehole diameter, fluid temperature, and fluid conductivity data. All four probes also acquired natural gamma (NG). The probes acquired data at up to 0.05 ft (0.015 m) sample rate. In addition, optical and/or acoustical televiewer logging was performed on the borings. The downhole geophysical survey results matched well with boring logs.

8. EXAMPLES OF FINDINGS FROM INTEGRATED GEOPHYSICAL AND GEOTECHNICAL STUDY

The main purpose of the integrated geophysical and geotechnical study was to evaluate the subsurface conditions that contribute to deteriorating seepage conditions in the western embankment. The following are two examples where findings from this integrated approach have enhanced the pre-investigation understanding of the factors contributing to the seepage conditions.

8.1 Example 1: V-4 Seepage Area

As excessive seepage was found on the western embankment since water impoundment in 1969, a French drain system was installed near Sta. 6+460 in 1973. This area is within a portion of the western embankment, where large cavities were encountered during construction and foundation treatment techniques included grouting, dental concrete, and concrete infilling of large cavities. V-4 area is also near the Georgetown Marl and Georgetown Limestone contact along the longitudinal profile and near multiple mapped faults. Figure 6 shows photographs of large cavities at Station 6+460 that were filled during construction. Figure 7 shows a map of foundation treatment in the western embankment.

Figure 6 : Photographs of Cavities Encountered at Station 6+460 During Construction

Two geologic transverse cross sections at Station 6+355 and 6+460 have been developed with crest, mid-slope, and downstream borings (Figures 8 and 9). Borings in V-4 area matched well with the understanding about this area. The crest borings indicate that the core portion of the dam is founded on limestone or dental concrete that was placed during construction. However, the mid-slope borings encountered three larger cavities with clay fill or clay and silt infill ranging between 27 feet and 46 feet. The downstream borings also encountered cavities.

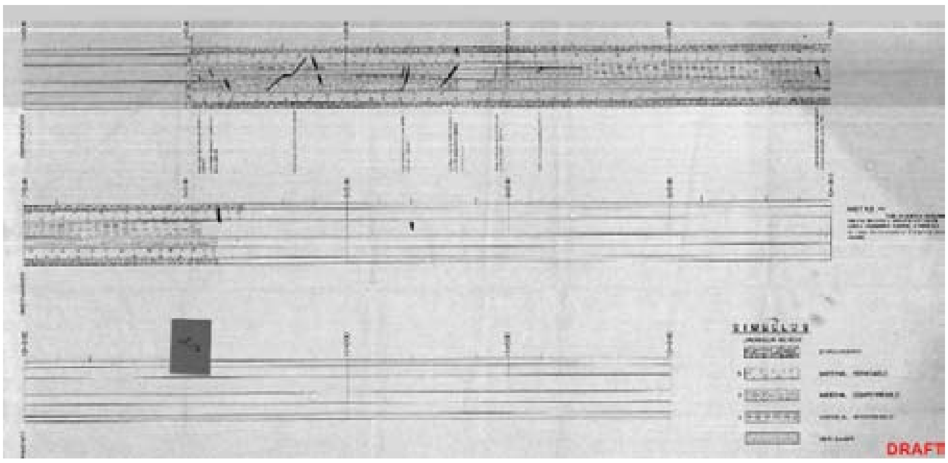

Figure 7 : Foundation Treatment Map for the Western Embankment

Downhole geophysical survey also provided valuable information about the cavities. The 360 degree profiles generated from televiewer were compared with caliper responses and distorted responses in calipers matched well with cavities identified from borings and televiewers. Figure 10 shows results of downhole geophysical survey results for Boring W-BV4-1, which is located in mid-slope and large cavities were encountered in this boring.

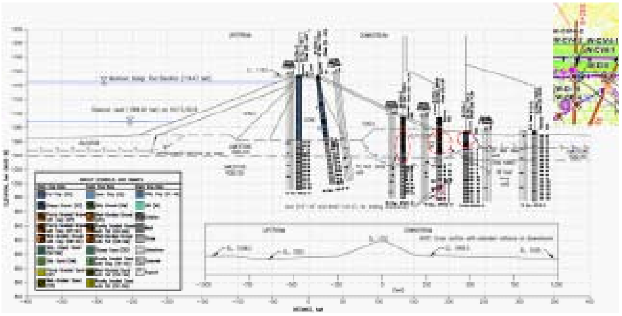

Figure 9 : Geologic Cross Section in V-4 Area (Station 6+355)

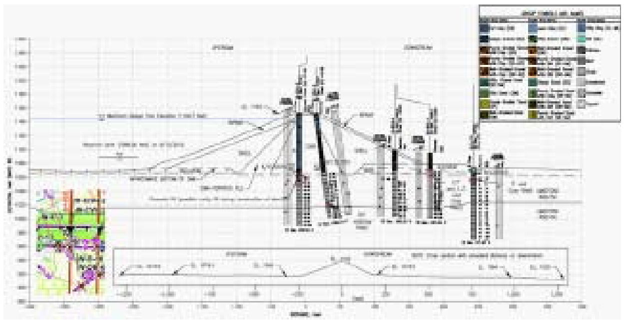

Figure 10 : Geologic Cross Section in V-4 Area (Station 6+460)

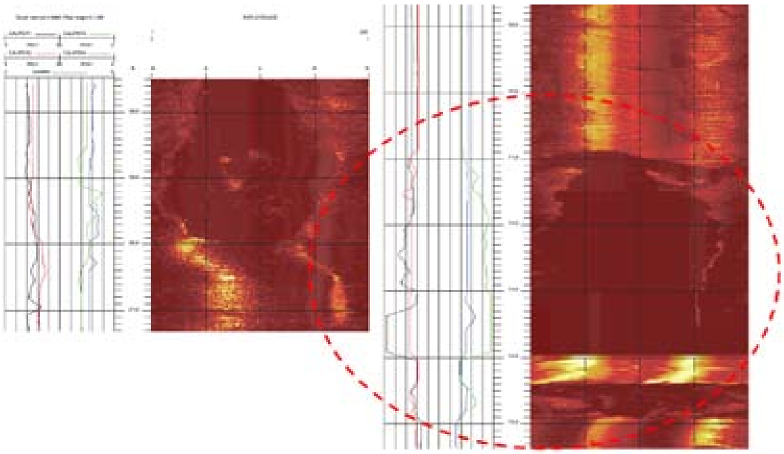

Figure 11 : Results of Caliper and Acoustic Televiewer for Boring W-BV4-1

8.2 Example 2: Station 7+121

Several sinkholes were observed in upstream of dam near this area. This section is located across upstream, embankment, and downstream borings that are near geophysical anomalies and may indicate a potential seepage path, if these anomalous zones are connected [A-42 (Rank 1) in upstream, A-4 (Rank 3) in embankment, and A-26 (Rank 1)]. A mapped south-west trending fault matches well with geophysical anomalies in upstream, embankment, and downstream locations. This section is also located within Station 5+520 and Station 8+100, an area where multiple foundation treatment techniques were used during construction (grouting, dental concrete between Station 5+520 and Station 6+725, and concrete infilling for large cavities). Recent grouting programs were implemented along the upstream toe (1998-six segments of the dam within Station 6+850 and Station 7+450) and embankment of the dam (1995-Station 6+850 and Station 7+450). Figure 12 shows the plan, geologic profile, and cross section with surface geophysical survey results (ERI and Microgravity) for Station 7+121 in upstream, crest, and downstream areas. Figure 13 shows a geologic cross section through Station 7+121.

Borings in upstream, crest, and downstream encountered cavities, which match well with surface geophysical survey, geologic mapping, and past performance history in this area.

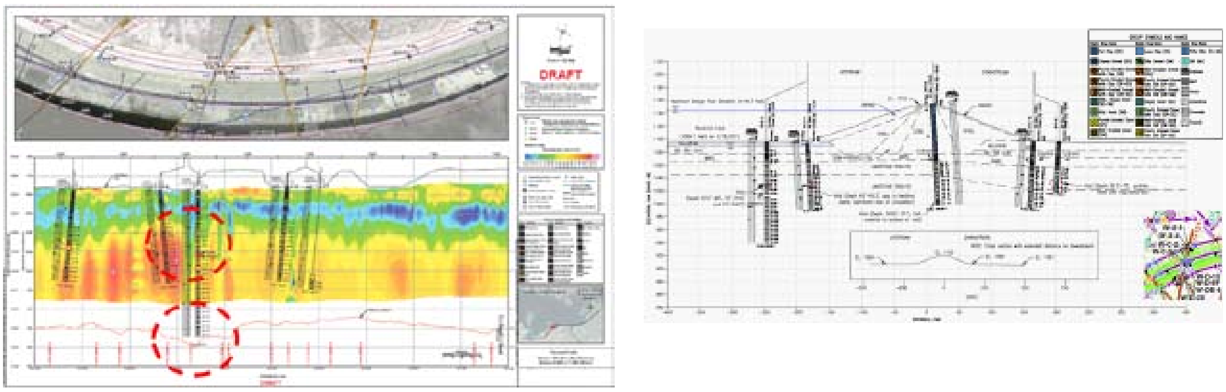

Figure 12: Geological, Geophysical Profile and cross section Near Station 7+121 through Dam Downstream

9. CONCLUSION

The integrated geologic and geophysical approach to conduct subsurface investigations in Karstic foundation has proven to provide reliable results and is highly recommended. The following are some observations based on the findings of the investigation program:

- The use of multiple techniques provides the investigator the use of the best tool for each stage of the investigation. Each technique provides a certain type of data, the summation of all the data provides for a strong interpretation of subsurface conditions.
- The approach provides for the progressive systematic and methodic evaluation of findings with each new finding validating or discarding previous assumptions and at the same time providing the basis for new interpretations.
- Sequencing the investigation is the key to optimize the use of the various techniques as some of them are more valuable from a more broad/general perspective (general seepage conditions) while others are more valuable when targeting very specific information (borings).
- Geophysical techniques provide reliable information, which is useful in selecting borings and understanding subsurface anomalies.