A GEOTECHNICAL CHARACTERIZATION OF THE EPIKARST AT THE CLEARWATER DAM SITE, WAYNE COUNTY, MISSOURI

A thesis submitted to Kent State University in partial fulfillment of the requirements for the degree of Master of Science

by
Kristen M. Enzweiler
August, 2012
Thesis written by
Kristen M. Enzweiler
B.S, Northern Kentucky University, 2006
M.S., Kent State University, 2012

Approved by

Dr. Abdul Shakoor, Advisor
Dr. Daniel Holm, Chair, Department of Geology
Raymond A. Craig, Associate Dean, College of Arts and Sciences
# TABLE OF CONTENTS

LIST OF FIGURES........................................................................................................... v

LIST OF TABLES............................................................................................................ ix

ACKNOWLEDGEMENTS............................................................................................... x

CHAPTER 1: SUMMARY................................................................................................. 1

CHAPTER 2: INTRODUCTION......................................................................................... 3

History of Clearwater Dam.......................................................................................... 3
Problems at Clearwater Dam....................................................................................... 7
Objectives....................................................................................................................... 9

CHAPTER 3: SITE GEOLOGY......................................................................................... 10

Geologic Setting........................................................................................................... 10
Karst Development...................................................................................................... 14
Epikarst......................................................................................................................... 17

CHAPTER 4: RESEARCH METHODOLOGY............................................................... 22

Field Investigations..................................................................................................... 22
Site Description........................................................................................................... 22
Sample Collection....................................................................................................... 24
Detailed Line Survey................................................................................................... 24
In-situ Permeability Testing........................................................................................ 24
Laboratory Investigation............................................................................................. 28
Absorption Test.......................................................................................................... 28
Specific Gravity.......................................................................................................... 30
Porosity......................................................................................................................... 31
Unconfined Compressive Strength Test...................................................................... 31
Direct Shear Test........................................................................................................ 32
Data Analysis............................................................................................................... 32

CHAPTER 5: RESULTS OF FIELD INVESTIGATIONS, LABORATORY TESTS AND DATA ANALYSIS ................................................................................................. 35

Results of Field Investigations.................................................................................... 35
Detailed Line Survey................................................................................................... 35
Permeability................................................................................................................ 37
Laboratory Results..................................................................................................... 41
Absorption .................................................................41
Specific Gravity..........................................................41
Porosity........................................................................43
Unconfined Compressive Strength..................................43
Shear Strength Parameters..........................................44
Data Analysis...............................................................44

CHAPTER 6: CURRENT REMEDIAL MEASURES..........................50
Seepage History...........................................................50
Remediation Process.....................................................53

CHAPTER 7: CONCLUSIONS....................................................58

REFERENCES.................................................................62

APPENDIX A: Dam Photographs.......................................65
APPENDIX B: Laboratory and Sample Photographs..............73
APPENDIX C: Laboratory Test Results..............................78
APPENDIX D: Borehole Photographs and Data....................83
LIST OF FIGURES

Figure 1: Location of Clearwater Dam in Missouri.................................................4

Figure 2: An overview of Clearwater Dam looking upstream, showing area of historical seepage between the valley and left abutment.................................................................6

Figure 3: An aerial view of the 2002 record high pool looking toward the left abutment...........................................8

Figure 4: Sinkhole on the upstream face of the dam..............................................8

Figure 5: Ozark physiographic province and subsections.....................................11

Figure 6: Stratigraphic column of Southeast Missouri........................................13

Figure 7: Map of Missouri lineaments.................................................................15

Figure 8: Major karst areas of the United States. Boundaries are generalized and some regions shown in solid black contain some non-karst areas........................................18

Figure 9: Conceptual karst hydrology.................................................................18

Figure 10: Principal structural and hydrologic features of epikarst......................19

Figure 11: Voids in epikarst outcrop.................................................................19

Figure 12: Map of Dam and “Epikarst Beach”..................................................23

Figure 13: View of dam from field site location on “Epikarst Beach”.................23

Figure 14: Typical outcrop showing epikarst formation at the top of the dolomite in (a) thick layers, (b) along joints and (c) bedding planes.........................................................25

Figure 15: Moderately weathered epikarst outcrop on the “Epikarst Beach”........26

Figure 16: Highly weathered epikarst rock with multiple voids.........................27

Figure 17: Location of sample collection on “Epikarst Beach”...........................29

Figure 18: Section of outcrop where detailed line survey was performed...........29

Figure 19: Unconfined compression testing machine.........................................33
Figure 20: Direct shear test apparatus..........................................................33
Figure 21: Conjugate joint set in the dolomite at the field site.........................36
Figure 22: Stereonet plot of joints from the “Epikarst Beach” site....................38
Figure 23: Stereonet of 55 joint measurements taken from the right abutment.....38
Figure 24: Diagram of the two solution features in the dam foundation near station 40+00........................................................................................................39
Figure 25: Random samples of compression tested epikarst showing variable strength of epikarst material. Also see Appendix B: Figures B-4 and B-5......................45
Figure 26: Direct shear test apparatus............................................................45
Figure 27: Sample in direct shear test apparatus before failure......................46
Figure 28: Sample in direct shear test apparatus after failure.........................46
Figure 29: Location of sinkhole and underlying solution features in plan and profile views...........................................................................................................52
Figure 30: View of work platform from right abutment. A-line and B-line production holes can be seen.................................................................55
Figure 31: Rotary drilling angled grout hole on the B-line...............................56
Figure 32: Work platform showing the angle of A-line and B-line holes...........57
Figure 33: A close-up of epikarst outcrop......................................................61
Figure 34: Two epikarst samples demonstrating different compressive strengths....61
Figure A-1: Dam site before construction.....................................................66
Figure A-2 Excavation of cutoff trench.........................................................67
Figure A-3: Open joint located in the cutoff trench foundation.......................68
Figure A-4: View from right abutment of impervious clay core and embankment fill…69
Figure A-5: View from left abutment of impervious clay core and embankment fill.....70
Figure A-6: View from left abutment of completed dam…………………………………………………………………………………71

Figure A-7: Original cross section of Clearwater Dam…………………………………………………………………………………………………………………………………………………71

Figure A-8: Current cross section of Clearwater Dam…………………………………………………………………………………………………………………………………………………72

Figure B-1: Field site showing epikarst in thick layers at the top of the approximate 15 ft high outcrop…………………………………………………………………………………………………………………………………………………74

Figure B-2: Field site showing epikarst formation at the top of the outcrop and along horizontal bedding planes…………………………………………………………………………………………………………………………………………………75

Figure B-3: Typical detailed line survey on epikarst outcrop……………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………………vii
Figure D-8: Drilling log showing cavities and fractured nature of the epikarst........91-98
LIST OF TABLES

Table 1: Summary of laboratory test results .............................................................. 42
Table 2: Rock mass rating classification parameters and ratings ............................ 48
Table 3: Calculated rock mass rating for epikarst material ..................................... 49
Table C-1: Absorption test results ........................................................................... 79
Table C-2: Results of specific gravity testing ........................................................ 80
Table C-3: Results of porosity calculations ............................................................. 80
Table C-4: Results of unconfined compression testing ........................................... 81
ACKNOWLEDGEMENTS

I thank Dr. Abdul Shakoor for his guidance throughout the completion of my graduate degree.
I would also like to thank Gannett Fleming, Inc and the Army Corps of Engineers for providing me with data and an opportunity to work and study at Clearwater Dam.

Finally, I thank my family for their love, support and encouragement.
CHAPTER 1

SUMMARY

The Clearwater Dam in Wayne County, Missouri, is a 154 foot (46.9 m) high zoned earth-fill structure constructed on Cambrian and Ordovician carbonate rocks, primarily for flood control. A sinkhole, 10 feet (3 m) across and 10 feet (3 m) deep, formed in January 2003 on the upstream face of the dam at an elevation of 570 feet (173.7 m). The sinkhole development was most likely a result of sediment loss through piping due to the epikarst solution features at the base of the dam. Epikarst is defined as the uppermost weathered zone of karstified rock with enhanced porosity and permeability compared to the underlying bulk rock. Epikarst formation progresses over time through stress release, weathering, and dissolution. The near surface weathered zone acts as a recharge zone for the underlying karst. The epikarst at the Clearwater Dam site is a highly variable zone. The zone spans a thickness of up to 100 feet (30.5 m) in the foundation of the dam. Upstream, the epikarst is exposed in an outcrop where it formed along the bedding planes, joints and top surface of the Potosi dolomite, roughly 30 feet (9.1 m) thick. These solution features and joints create serious seepage and piping problems for the dam. The dam has undergone remedial measures to install a cutoff wall to block the flow of water through the open cavities.
This study investigated the nature and causes of seepage problems in light of geologic conditions present at the Clearwater Dam site by evaluating outcrops and borehole logs provided by the U.S. Army Corps of Engineers and Gannett Fleming, Inc. It also characterized the epikarst layer in the dam foundation in terms of its geologic, hydrologic, and engineering properties. A representative site was chosen upstream from the right abutment of the dam which contained an outcropping of the Potosi dolomite and the overlying epikarst material. This site is locally known as “epikarst beach”. A detailed line survey was conducted to measure the orientation and other aspects of the joints. Epikarst material from the site was collected to perform absorption tests, specific gravity tests, unconfined compressive strength tests and direct shear tests. Laboratory testing revealed a much weaker and more porous rock than typical dolomite. Epikarst porosity is roughly 50%, specific gravity is half of standard dolomite, and absorption is twice that of dolomite. The unconfined compressive strength and shear strength parameters were significantly lower than dolomite, demonstrating that the epikarst is at least 50% weaker. However, there was some variation of strength between the different samples that may be attributed to the amount of chert and voids in the samples.
CHAPTER 2

INTRODUCTION

2.1 History of Clearwater Dam

Clearwater Dam is located on the Black River in Wayne and Reynolds Counties in southeast Missouri (Figure 1). It is in the rural eastern part of the Ozark Plateau, close to the New Madrid Fault Zone. Dam construction began in 1940 but was not completed until 1948 due to World War II (see Appendix A: Figures A-1 – A-6 for dam construction pictures). The dam is a rolled earthfill embankment, containing 5.5 million cubic yards of fill material, with an inclined clay core (Harris and Van Cleave, 2007). The core consists of clay and silt obtained from the riverbed. The upstream slope of the core is 1H:1V while the downstream slope is 0.5H:1V. The shell material of pervious gravelly sands was also obtained from the riverbed alluvium. The upstream embankment slope was initially constructed at 3H:1V, which was later modified to address seepage problems (see below), and the downstream slope was constructed at 2.5H:1V (see Appendix A: Figure A-7 for original cross section of the dam) (Bradley et al., 2008). The dam has a crest length of 4,225 ft (1287.8 m) and it rises 154 ft (46.9 m) from the stream bed. The right abutment contains the controlled outlet works consisting of an intake structure with control tower, a tunnel, a stilling basin and a discharge channel. The dam’s
Figure 1: Location of Clearwater Dam in Missouri.
main purpose is to mitigate flooding; however, the reservoir is also used for recreation and wildlife conservation (Figure 2).

The conservation pool has a maximum depth of 40 ft (12.2 m), surface area of 1,630 acres, and a drainage basin of 898 square miles (2,325.8 km²). The top of the conservation pool at 494 ft (150.6 m) elevation provides 21,920 acre-ft (27,038,320 m³) of storage, and 391,780 acre-ft (483,260,630 m³) of flood storage between elevations 494 ft-567 ft (150.6 m - 172.8 m) (conservation pool to the top of the flood pool) (Harris and Van Cleave, 2007).

During construction of the dam, the dolomite bedrock was found to be highly weathered and fractured near the surface and identified as karstic for its solubility and ability to form crevices and caverns. The uppermost weathered zone of this karstified rock was later identified as epikarst with enhanced porosity and permeability compared to the underlying bulk rock. This zone has since been the leading cause of uncontrolled seepage below Clearwater Dam. With knowledge of the possible seepage problems, a grout curtain was constructed only in the valley portion of the core trench which ended short of the left abutment. An impervious seepage blanket was constructed on the upstream face of the left abutment. However, the left abutment seepage blanket and the valley grout curtain did not overlap. Therefore, a section of the dam was left unprotected against seepage between the blanket and grout curtain which became an area of historical seepage problems for the dam (Figure 2). At the time of construction, it was thought that seepage paths would be limited to the bedrock and overburden material of the dam foundation, but seepage amounts could not be known until after the impoundment of the
Figure 2: An overview of Clearwater Dam looking upstream, showing area of historical seepage between the valley and left abutment (USACE-b, 2010).
reservoir. Therefore, it was planned that further treatment would occur in the future, when and where it was needed (U.S. Army Corps of Engineers, 1989, 1991). Numerous piezometers were installed to monitor seepage. Later remedial measures included two subsurface drainage systems installed downstream of the left abutment in 1972 and 1980 to relieve pressure, lower the phreatic line, and prevent underseepage from emerging above ground downstream of the dam. In 1988, an upstream seepage berm and impervious seepage blanket on the upstream face, up to elevation 575 ft (175.3 m) were constructed to lengthen the flow paths both vertically and horizontally. This altered the upstream slope to 4H:1V (Harris and Van Cleave, 2007), although it did not resolve the issues.

2.2 Problems at Clearwater Dam

Seepage through the epikarst layer has been a persistent problem at Clearwater Dam since it’s completion in 1948. Regardless of the added seepage protection, a serious problem developed in 2002-2003. During May 2002, a record-high pool elevation of 566.7 ft (172.7 m) was recorded (Figure 3). This elevation is only 0.3 ft (9.1 cm) below the top of the flood pool elevation. The Pool of Record (POR) resulted from a 60-70 year storm event with average rainfall of 20 inches (50.8 cm) over the drainage basin (Bradley et al., 2008). Eight months after the POR, on January 13, 2003, a sinkhole was discovered on the upstream face of the dam at elevation 573 ft (174.7 m), 7 ft (2.1 m) above the POR elevation (Figure 4). The sinkhole, 10 ft (3 m) in diameter and 10 ft (3 m) deep, was most likely caused by piping through the solution cavities in the foundation of the dam. USACE ranks the risk analysis of dams from I-V based on
Figure 3: An aerial view of the 2002 record high pool looking toward the left abutment (USACE-c, 2010).

Figure 4: Sinkhole on the upstream face of the dam (USACE-d, 2010).
consequence data and engineering ratings of embankments, foundations, abutments, spillways, reservoirs, and any other necessary features. The U.S. Army Corps of Engineers (USACE) classified the dam as a Dam Safety Action Class I dam. An Action Class I dam is classified as urgent and compelling (unsafe). This class of dam is critically near failure or at an extremely high risk where progression toward failure is confirmed to be taking place under normal operations and there are loss of life or economic consequences, with the probability of failure being extremely high. Class I dams, such as Clearwater Dam, require immediate action and implementation of risk reduction measures (McClenathan et al., 2008).

Until a permanent solution is completed, there is a risk of more solutional features forming in the karst environment leading to piping of the embankment into the karstic dolomite foundation, especially through the epikarst zone, creating new sinkholes and overtopping of the impervious clay blanket should the reservoir exceed an elevation of 575 ft (175.3 m).

2.3 Objectives

The objectives of this study were as follows:

1. To investigate the nature and causes of seepage problems in light of geologic conditions present at the Clearwater Dam site.

2. To characterize the epikarst layer in the dam foundation in terms of its geologic, hydrologic, and engineering properties.
CHAPTER 3

SITE GEOLOGY

3.1 Geologic Setting

Clearwater Dam is located within the broad asymmetrical dome of the Ozark Plateau Physiographic Province. The Ozarks include four sub-sections: The Salem Plateau, Springfield Plateau, St. Francois Mountains, and the Boston Mountains (Figure 5). The St. Francois Mountains comprise the Precambrian igneous core of the Ozarks. The Salem Plateau is mainly composed of Cambrian and Ordovician carbonates, with a few clastics. A band of resistant Mississippian carbonates forms the Springfield Plateau. The Boston Mountains consist of Mississippian strata capped by Pennsylvanian sandstone (George, 2007). The dam is founded on the Cambrian Potosi Dolomite within the Salem Plateau. The Potosi Dolomite is 500 ft (152.4 m) thick in the area of the dam with massive thick beds of dolomite containing small quartz crystals and red clays (Unklesbay and Vineyard, 1992). This dolomite was formed through replacement of the original calcium carbonate sediment by dolomite. Dolomitization occurred along fracture surfaces as the carbonate beds underwent solutional brecciation followed by compaction (Howe, 1968). The Potosi is a part of the Upper Cambrian Series that formed during a general transgression over the Precambrian igneous knobs. The series consists of six formations: Lamotte Formation [200-300 ft (61-91.4 m) thick sandstone], Bonneterre Formation [400-1500 ft (121.9-457.2 m) thick limestone and dolomite], Davis Formation
Figure 5: Ozark physiographic province and subsections (George, 2007).
[200 ft (61 m) thick alternating limestone and shale], Derby-Doe Run Formation [150 ft. (45.7 m) thick sandy dolomite with siltstone and shale], Potosi Formation [500 ft (152.4 m) thick dolomite], and Eminence Formation [350 ft (106.7 m) thick sandy dolomite with chert] (Unklesbay and Vineyard, 1992). In the vicinity of the dam, the Precambrian basement rock may be around 1,000 ft (304.8 m) below the dam crest (Figure 6) (Kisvarsanyi, 1984). Roughly 60 ft (18.3 m) of residuum, mostly from cherty dolomite, and alluvium from igneous and sedimentary sources overlie the bedrock in the area of Clearwater Dam (Pratt et al., 1992).

After the formation of the Potosi dolomite, there were five major episodes of deformation. The first was during the Upper Ordovician as there was minor uplift of the Ozark dome when the eastern United States collided with Africa forming the Appalachian Mountains. The second occurred during the Pre-Mississippian. The third period of major deformation occurred at the end of the Mississippian during the Acadian Orogeny to the northeast. It was during this time that the seas retreated and karstification began. The next deformation occurred Post-Pennsylvanian during the formation of the Ouachita Mountain range to the south as South America ran into North America. The final deformation occurred during the Tertiary. Each of these periods resulted in a renewed uplift of the Ozark area (Schaper, 2009). Seismic activity suggests there is continued uplift of the Ozark dome today (George, 2007).
Figure 6: Stratigraphic Column of Southeast Missouri.
The Ozarks are noted for having well developed karst across most of the area. Karst is predominantly found in the carbonate Cambrian bedrock. An important part of karst development is structural controls including amount of structural deformation and presence of open channels in the rock. Structural deformation affecting the Potosi dolomite includes the five episodes listed above. Bedding dip is generally low (<5°) away from the center of the dome (George, 2007). At the dam site, bedding dips towards the south and strikes east-west (U.S. Army Corps of Engineers, 2008). Other structural features such as faults, joints, and lineaments (Figure 7) enhance surface weathering and permeability, aiding in karst formation (George, 2007). Missouri’s major structural grain trends in a northwest-southeast pattern. Orientation of faults and joints in the brittle older rocks to the south and major fold axes in the younger rocks in the north show this structural trend. A secondary northeast-southwest pattern is also evident in the area (McCracken, 1971).

3.2 Karst Development

The plateau region of east-central Missouri is one of the five general areas of concentrated karst development in the United States (Figure 8). Karst develops in rocks that are particularly susceptible to solution action which can enlarge and create cavities in the rocks. This leads to interconnected voids which funnel subsurface water into an underground drainage system. The development of karst is dependent on several factors including porosity and permeability, lithology and the solution process (Ritter et al., 2002).
Figure 7: Map of Missouri lineaments (George, 2007).
The porosity and permeability of the rock helps determine the development of karst. Highly porous and permeable rocks speed up the solution process for karst development by allowing more water to come into contact with the soluble rock. The pattern of openings in the rock along bedding planes or fractures, like joints and fault zones (secondary porosity), is probably the most important factor of karstification because they increase porosity and permeability (Fetter, 2001). Solution features are common in the Potosi dolomite. Jointing is intense with major joints generally striking east to west (25° to 44° from the centerline of the dam) and secondary joints running perpendicular to the dam centerline. The joints dip nearly vertically and are extremely weathered in the Potosi Dolomite (U.S. Army Corps of Engineers, 2008).

The abundance of carbonate rock in the area leads to the development of karst topography below the dam. Dolomite, which comprises most of the rock units below the dam, is highly soluble. As water was introduced into the rock through joints and fractures, the dolomite was slowly dissolved and the sizes of the joints increased. As the joints enlarged, they became interconnected, increasing the flow of water (Figure 9). Over time, this process has led to differential dissolution below the dam, resulting in caverns, enlarged joints and an overall deteriorated rock. While grouting the sinkhole in 2003, a cavity was found 30 ft (9.1 m) below the top of rock extending approximately 120 ft (36.5 m) deep (U.S. Army Corps of Engineers, 2008). Near Clearwater Dam, subsurface drainage is significant, emphasized by cavities and large springs present in the region (Missouri Department of Natural Resources, 1995). Groundwater levels are influenced by both the reservoir and precipitation. When the reservoir remains at
conservation levels, the groundwater grades from the pool to the river level. However, precipitation and high pool levels can quickly increase the groundwater levels, especially in the area of historical seepage near the left abutment. Solutioning is particularly extensive within the highly fractured Potosi dolomite and the contacts between the formations (U.S. Army Corps of Engineers, 2008). The Elvins Group comprised of shaley dolomite of the Derby-Doerun Formation and dolomitic shale of the Davis Formation is absent below the dam. In its place is a “cavernous zone” 25 ft (7.6 m) thick between the Potosi Dolomite and Bonneterre Formation (U.S. Army Corps of Engineers, 1977).

3.3 Epikarst

Epikarst is defined as the uppermost weathered zone of karstified carbonate rock with enhanced porosity and permeability compared to the surrounding bulk rock. It works to store and filter water into the vadose zone through joints and fissures. Epikarst formation progresses over time through stress release, weathering, and dissolution. The near surface weathered zone acts as a recharge zone for the underlying karst (Klimchouk, 2004).

The concept of an “epikarst zone” performing functions for karst systems began in the 1970’s. The “epikarst zone” includes the karstified carbonate rock and perched aquifer within it above the vadose zone. The epikarst zone formation varies in extent and development based on several factors. An epikarst zone is characterized by its structural features, location, origin, hydrologic function and roles in the overall karst system, and its morphogenic role (Figure 10) (Klimchouk, 2004).
Figure 8: Major karst areas of the United States. Boundaries are generalized and some regions shown in solid black contain some non-karst areas (Ritter et al., 2002).

Figure 9: Conceptual karst hydrology (Ritter et al., 2002).
Figure 10: Principal structural and hydrologic features of epikarst (Klimchouk, 2004).

Figure 11: Voids in epikarst outcrop.
Structural features of epikarst zones include fissure networks in the shallow subsurface which are closely spaced and continuous. Figure 11 illustrates a void formed along bedding planes and joints within the epikarst at the field site. The porosity of epikarst is typically one to four orders of magnitude more than the fracture and solutional porosity in the bulk rock below (Klimchouk, 2004). The lower boundary of the zone is usually irregular based on relief, lithostratigraphy, and geologic structure. The epikarst zone thickness is usually up to 50 ft (15 m). The epikarst at the field site could be seen along the full extent of the 30 ft (9.1 m) outcrops. However, below Clearwater Dam the epikarst is generally 100 ft (30.5 m) thick. Epikarst is mostly located just below the soil. However, it can be exposed at the surface, such as at the “Epikarst Beach”. The development of epikarst can begin as a caprock is removed from underlying karst rock. Epikarst begins to form when the karst is exposed at the surface to weathering or when covered by regolith, by chemical weathering. This must take place in the vadose zone to allow free draining vertical percolation through the already karstified rock.

While dissolution is often considered the primary factor in epikarst development, the pathways formed by stress release and weathering are just as necessary. Stress release and weathering provide increased near surface porosity by forming or enhancing joints, bedding planes, and fissure frequency and connectivity. The distance, depth, and degree of epikarst development can vary over an area. Gannett Fleming found the epikarst layer extended 2,000 ft (609.6 m) from the left abutment toward the valley center and 150 ft (45.7 m) from the right abutment toward the valley center along the grout curtain alignment below the dam (Knight et al., 2010). Essentially, the epikarst zone
functions to store water and direct it into the karst rock through structural channels to continue dissolution and weathering to further the development of the system (Klimchouk, 2004).
CHAPTER 4

RESEARCH METHODOLOGY

4.1 Field Investigations

4.1.1 Site Description

The study site where field data and epikarst samples were collected is known as the “Epikarst Beach”. The site is located approximately 1.1 miles (1.8 km) upstream from the right abutment. The site can be reached driving southwest across the dam on the HH highway, continuing about half a mile (0.8 km) from the dam and turning right onto the road designated as RA. After 1.25 miles (2 km), RA dead ends into Clearwater Lake and Epikarst Beach (Figure 12 and 13). The upstream side of the outcrop is approximately 15-30 ft (4.6-9.1 m) high consisting of intact dolomite layers interspersed with epikarst material, chert, and quartz. The dolomite has roughly 2-3 ft (0.6-0.9 m) thick beds. The outcrop surface is irregular due to solution weathering. The epikarst material appears to be present in four forms: 1) relatively thick layers [1-2 ft (0.3-0.6 m)] at the top of the outcrop; 2) relatively thin layers along bedding planes; 3) as endocrustations- covering the surface of the dolomite; and 4) along joints (Figure 14). Figures 14-16 show the variability of epikarst outcrops at the study site. Roughly 15-35% of the outcrop is epikarst. The outcrop contains abundant growths of siliceous material in both crystalline
Figure 12: Map of dam and “Epikarst Beach.”

Figure 13: View of dam from field site location on “Epikarst Beach”.
and non crystalline form. The dolomite bedding is nearly horizontal (see Appendix B: Figures B-1 – B-4 for additional epikarst outcrops from the field site).

4.1.2 Sample collection

Representative samples of epikarst, from extremely vuggy to fairly solid, were collected from the downstream side of the outcrop (Figure 17). More than two dozen epikarst samples of at least 1ft x 0.5ft x 0.5ft (30.5cm x 15.2cm x 15.2cm) dimensions were collected and transported back to Kent State University for laboratory testing.

4.1.3 Detailed Line Survey

A detailed line survey (Figure 18), as proposed by Piteau and Martin (1973), was conducted to measure the orientation (strike and dip) and other aspects (continuity, spacing, surface irregularity, infilling material, and aperture) of the joints. Three detailed line surveys were conducted by stretching a 50 ft (15.2 m) long tape measure along the face of an outcrop and recording all of the joints that intersected the tape. Outcrop faces as well as bedding planes were noted along with the joints.

4.1.4 In-Situ Permeability Test

The permeability test was conducted by Gannett Fleming and recorded as Lugeon values. Lugeon values are measured as 1 liter of water per meter of length per minute at 10 bars pressure. One Lugeon equates to $1.3 \times 10^{-5}$ cm/sec. Gannett Fleming drilled holes into the dam embankment from a work platform at elevation 576 ft (175.6 m). Each hole was water tested in 10 ft (3 m) stages by sealing off the remaining length of the hole, pumping water under pressure, and recording the volume of water entering the hole.
Figure 14: Typical outcrop showing epikarst formation at the top of the dolomite in (a) thick layers, (b) along joints and (c) bedding planes.
Figure 15: Moderately weathered epikarst outcrop on the “Epikarst Beach”.
Figure 16: Highly weathered epikarst rock with multiple voids.
over a few minutes. Water testing was preformed to a depth of 245 ft (74.7 m) from the
platform elevation. Field permeability testing is further explained in chapter five.

Permeability was also calculated using the cubic law. The cubic law equation is
used to calculate flow in a set of parallel fractures. This equation simplifies the real life
conditions by assuming laminar flow through evenly spaced smooth-walled planar
fractures with consistent aperture (Fitts, 2002). The equation for permeability is as
follows:

\[ Permeability, K_f = \left( \frac{\rho_w g b^3}{12 \mu s} \right) \cos \theta_f \]  

where \( \rho_w \) is the density of water, \( g \) is gravity acceleration, \( \mu \) is the dynamic viscosity of water, \( b \) is
joint aperture, \( \theta_f \) is fracture orientation measured from the direction of flow, and \( s \) is fracture
spacing (Schwartz and Zhang, 2003). The permeability determined in the field was compared to
the permeability calculated from the equation above.

4.2 Laboratory Investigations

Laboratory tests were performed to determine the engineering properties of
epikarst material. The tests were performed according to the American Society for
Testing and Materials (ASTM) standards (ASTM, 1996), where applicable. Porosity and
absorption were determined using phase relations (Holtz & Kovacs, 1981).

4.2.1 Absorption Test

The absorption of a sample is determined by subtracting the dry weight \( (W_d) \) from
the saturated weight \( (W_s) \) then dividing by the dry weight of the sample. This is then
Figure 17: Location of sample collection on “Epikarst Beach”.

Figure 18: Section of outcrop where detailed line survey was performed.
multiplied by 100 to express the value as a percent. The equation of absorption is as follows:

$$Absorption = \left( \frac{W_s - W_d}{W_d} \right) \times 100$$  \[2\]

The saturated weight is determined by soaking a sample in water for 24 hours and weighing the saturated, surface dried sample. Dry weight is the weight of the sample after drying in an oven at 105°C for 24 hours. The absorption test (ASTM C-97/97M) was performed on 15 randomly cut epikarst samples. Absorption indicates the volume of voids in a rock to the volume of solid material (West, 1995). Absorption is related to the strength of the rock. A higher absorption implies more voids which indicates a weaker rock (Shakoor and Bonelli, 1991).

### 4.2.2 Specific Gravity

The specific gravity of a sample is determined by subtracting the submerged weight from the saturated weight ($W_{sat} - W_{sub}$) then dividing that into the dry weight of the sample ($W_d$). The equation for specific gravity is as follows:

$$Specific \ Gravity = \frac{W_d}{W_{sat} - W_{sub}}$$  \[3\]

The dry and saturated weights of the sample were previously found during the absorption test (ASTM C-97/97M). The submerged weight was calculated by submerging an empty can, suspended from a scale, in water. Once the scale was zeroed, the sample was placed in the can and weighed to get the submerged weight. This test was performed on nine samples. Specific gravity expresses the ratio between the weight of the rock and that of
an equal volume of water. The specific gravity can be multiplied by the unit weight of water to give the unit weight or bulk density ($\gamma_m$) of the rock (West, 1995).

4.2.3 Porosity

Porosity is the percentage of void space in a rock. Porosity can be calculated as a percentage by subtracting from 1 the bulk density ($\gamma_m$) divided by the specific gravity (Gs) and then multiplying by 100 (West, 1995).

$$\text{Porosity, } n = \left(1 - \frac{\gamma_m}{Gs}\right) \times 100$$  \[4\]

A highly porous rock has more voids and therefore implies a weaker rock.

4.2.4 Unconfined Compressive Strength Test

The unconfined compression test (ASTM D-7012) is a common test used to measure the strength of a rock. Since cores of the epikarst could not be obtained, samples of epikarst retrieved were cut into twenty 2 inch x 2 inch x 2 inch (5.1cm x 5.1cm x 5.1cm) cubes. Each cube was placed in a Forney unconfined compression test loading frame (Figure 19). The cube was placed on a steel platen directly beneath a steel piston. The lower steel platen was raised until the top of the cube sample was in contact with the piston. A continuously increasing load was applied at a constant rate to the sample so that it failed within 5-15 minutes. The peak load was recorded at the time of failure and divided by the cross-sectional area of the sample to find the unconfined compressive strength. The samples were prepared as cubes (height to diameter ratio of 1) and not as cylinders as suggested by ASTM. Therefore, a correction factor of 0.85 was applied to the unconfined compressive strength test results (Elwell and Fu, 1995).
4.2.5 Direct Shear Test

Direct shear test is a common test performed to determine values of cohesion and friction. This test was performed according to the specifications outlined in ASTM D-5607 (ASTM, 1996). A 5 inch x 2 inch x 2 inch (12.7cm x 5.1cm x 5.1cm) block was cut from the collected epikarst samples and placed vertically in the direct shear apparatus (Figure 20). The cut sample was encompassed by two cylinders of cement in order to hold the sample in place in the bottom ring and to apply a load to the top ring. The rings containing the sample were separated by a layer of clay in the center to allow the failure plane to propagate. Shear and normal loads were applied to the top cylinder (containing the upper half of the sample) until failure. The shear stress at the time of failure was recorded. This procedure was repeated for three samples per test at different normal loads.

4.3 Data Analysis

Engineering property data obtained from laboratory investigations was presented in the form of tables and graphs displaying the ranges, means, and standard deviation values for each property. The field data from borehole logs was used to determine the variability in the thickness of the epikarst layer along the dam axis as well as the variability of its structural features such as rock quality designation (RQD), presence of voids, joint characteristics, etc. RQD is a measure of the fracture frequency in a rock. It is recorded as a percent by summing the length of core pieces greater than four inches (10cm) and dividing it by the total length of the core run. The data from detail line surveys performed on the epikarst rock outcrops was analyzed using the stereographic
Figure 19: Unconfined compression testing machine.

Figure 20: Direct shear test apparatus.
projection techniques. The purpose was to determine the principle joint sets present in the surface outcrops of the epikarst material and use this information to explain epikarst development. The field data about other aspects of the joints was compared with the corresponding data obtained from the rock core. The laboratory and field data regarding the epikarst was analyzed to evaluate its engineering and hydrologic behavior. The results of the detailed line survey, strength, and RQD data were used to determine the rock mass rating (RMR) for epikarst according to Bieniawski’s classification system (Bieniawski, 1973). Bieniawski’s rock mass rating classification system divides a rock mass into five classes. The classes range from I (very good rock) to V (very poor rock). The class of a rock was determined by several parameters including intact rock strength, RQD, discontinuity spacing and orientation, and groundwater. Each parameter had a range of values with rating number assigned to each one. Each parameter’s determined rating number was added together to determine rock mass rating and the corresponding description.
CHAPTER 5

RESULTS OF FIELD INVESTIGATIONS, LABORATORY TESTS AND DATA ANALYSIS

5.1 Results of Field Investigations

5.1.1 Detailed Line Survey

Measurements from the three detailed line surveys were averaged for joint spacing, joint aperture, and joint continuity (Figure 21) (see Appendix B: Figure B-3 for typical outcrop measured by detailed line survey). Joint spacing along the epikarst outcrop at the Epikarst Beach ranges from 6 inches (15.2 cm) to 2 ft (0.6 m) with an average of 1.25 ft (0.4 m). Joint aperture ranges from less than 1/2 inch (1.3 cm) to almost 3 inches (7.6 cm) with an average of 1 inch (2.5 cm) aperture. The continuity ranges from 1 ft to 15 ft (0.3-4.6 m), with an average of 3.5 ft (1 m). All joint orientations were plotted on a stereonet (Figure 22). Based on the analysis of the orientations of all recorded joints on the outcrop, two major joint sets exist that are oriented N75°E and N37°W with near vertical dips of 80°NW and 84°SW, respectively.

Joint measurements were also taken by Gannett Fleming along the right abutment, both upstream and downstream of the dam, as well as below the dam using a Robertson device lowered into boreholes. Those 55 joint measurements, when plotted on a stereonet (Figure 23) indicate two dominant, near vertical, joint sets trending N74°E and
Figure 21: Conjugate joint set in the dolomite at the field site.
The two large solution features identified below the dam in the area of the sinkhole, trending N80°E and N57°W, appear to follow the dominant joint pattern seen in Figures 20 and 21. The dam axis is aligned N43°E (Figure 24).

The joint sets measured at the field site in this study and those measured by Gannett Fleming on the right abutment are nearly identical as seen in the two stereonet plots (Figures 22 and 23). This suggests these are tectonic joints produced by regional stresses. These continuous joints provide seepage an easier path from upstream to downstream through the right abutment. The two solution features below the dam trend similarly to the two joint sets found on the right abutment and the right bank. While the right abutment has not been an historical location for major seepage, the presence of these joints suggest that the remainder of the dam foundation and left abutment, where seepage has traditionally been concentrated, are similarly jointed (Roman, 2004). The orientation of the jointing at the dam site contributed to the formation of epikarst and seepage problems at the dam. The closely spaced open joints provide a means for water to encounter the Potosi dolomite at depths to continue the solution process as well as a near perpendicular path below the dam for seepage to occur.

5.1.2 Permeability

The permeability determined by Gannett Fleming from the water tests is 20-200 Lugeon (Lu). This is equivalent to 2.6 x 10^{-4} cm/sec to 2.6 x 10^{-3} cm/sec. The closure criteria for permeability on a grouted hole was 3x10^{-5} cm/sec (3 Lu). Therefore, the rock needed to be treated to prevent seepage and piping through the epikarst and joints. Gannett Fleming noted a correlation between core recovery/RQD and permeability.
Figure 22: Stereonet plot of joints from the Epikarst Beach site.

Figure 23: Stereonet of 55 joint measurements taken from the right abutment (Roman, 2004).
Figure 24: Diagram of the two solution features in the dam foundation near station 40+00 (Roman, 2004).
As the core recovery and RQD values increased, permeability values decreased. Sections of higher core loss correspond to higher permeability values (Knight & Hockenberry, 2008). The higher permeability in the epikarst increased the flow of water through the bedrock thereby increasing the advancement of epikarst development and further weakening the rock.

The cubic law equation was also used to calculate permeability in order to compare it with the results of the field permeability tests. The joint values used in the equation were determined from the average joint spacing, aperture and orientation measured with the detailed line survey ($b = 0.025 \text{ m}$, $s = 0.4 \text{ m}$, $\theta = 10^\circ$). The water properties were determined by assuming a water temperature of 10°C (50°F) (Fetter, 2001). These values resulted in a calculated permeability of 26 m/s which was five to six orders of magnitude greater than the permeability determined by field testing ($2.6 \times 10^{-5}$ to $2.6 \times 10^{-6} \text{ m/s}$). This discrepancy was likely due to the simplification of the cubic law equation. The equation assumes a laminar flow through evenly spaced smooth-walled planar features. Joints within the epikarst rock are not evenly spaced with constant apertures and they are not straight or smooth-sided. There are also multiple joint sets with different orientations that would alter the results. The actual rock conditions would result in turbulent, not laminar flow, due to greater friction through a more tortuous path. Also, this equation only considers flow through fractures, but not through the porous rock itself. To better calculate the nature of flow through a complex network of fractures and porous rock, such as epikarst, sophisticated computer models were needed (Schwartz and Zhang, 2003), however, this was beyond the scope of this research. By comparing the
above methods and results for determining permeability, it was found that the permeability determined by Gannett Fleming in the field is a better representation of flow through the epikarst.

5.2 Laboratory Test Results

5.2.1 Absorption

Absorption was calculated for 15 random samples of epikarst. Absorption values ranged from 6%-15% in the samples tested. The average absorption is 10.9% and has a standard deviation of 2.9% (Table 1). Average absorption values for dolomites are 1-5%. Epikarst is at least twice as absorbent as typical dolomite implying the void space in epikarst is increased to create more surface area in contact with water, decreasing the volume of solid material and, therefore, decreasing the strength of the rock (see Table C-1 in Appendix C for absorption results).

5.2.2 Specific Gravity

Specific gravity of the epikarst, measured on samples, ranges from 1.6 to 2.0 with an average of 1.7. The standard deviation is 0.12 (Table 1). The typical specific gravity of dolomite is 2.8-2.9 (West, 1995). This shows the density of epikarst (density is specific gravity multiplied by the density of water) is generally half that of the parent rock. As epikarst development increases, the ratio of solid dolomite to porous vuggy dolomite decreases. This also leads to a weaker rock than non-karsted dolomite. Table C-2 in Appendix C provides specific gravity results.
Table 1: Summary of laboratory test results.

<table>
<thead>
<tr>
<th>Test</th>
<th>Range</th>
<th>Average</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absorption</td>
<td>6-15%</td>
<td>10.9%</td>
<td>2.9%</td>
</tr>
<tr>
<td>Specific Gravity</td>
<td>1.6-2.0</td>
<td>1.7</td>
<td>0.12</td>
</tr>
<tr>
<td>Porosity</td>
<td>44-52%</td>
<td>47.8%</td>
<td>2.4%</td>
</tr>
<tr>
<td>Unconfined Compressive Strength</td>
<td>11-148.8 kg/cm² (156-2111 psi)</td>
<td>46.6 kg/cm² (661 psi)</td>
<td>37.5 kg/cm² (532 psi)</td>
</tr>
<tr>
<td>Direct Shear Test cohesion and friction</td>
<td>225-500 psi 10°-20°</td>
<td>362.5 psi 15°</td>
<td>194.5 psi 7°</td>
</tr>
</tbody>
</table>
5.2.3 Porosity

The porosity of nine samples was calculated using the specific gravity, submerged weight, and total volume of each sample. The range of porosity is 44-52%. Average porosity of the epikarst samples is 47.8% with a standard deviation of 2.4% (Table 1). Nearly half of the epikarst volume is occupied by voids which decrease the strength and increase the presence of water to further dissolution. See Table C-3 in Appendix C for all porosity results.

5.2.4 Unconfined Compressive Strength

Unconfined compressive strength of a rock is the most frequently used property in engineering practice. Other index or engineering properties of rock are related to unconfined compressive strength (Bieniawski, 1973; Shakoor and Bonelli, 1991). Compressive strength of epikarst ranges from 156 psi (11 kg/cm²) to 2,111 psi (149 kg/cm²), (Figure 25), with an average unconfined compressive strength is 661 psi (46.6 kg/cm²) (Table 1). Two random samples of compression tested epikarst depicting the strength variability of the material are shown in Figure 25. Unconfined compressive strength for dolomite typically ranges from 11,000 to 34,700 psi (776-2,447 kg/cm²) (West, 1995). While the strength of the epikarst tested varied, reaching strength values up to 2,484 psi (175 kg/cm²), it is on average only 7% the strength of typical dolomite. The variations in compressive strength are attributed to the degree of vugginess and the amount of quartz present in each sample. Epikarst development can vary across a location depending on jointing and composition. Not all samples collected contained the same amount of quartz or experienced the same extent of solutioning. Samples
containing more voids and less quartz were generally weaker than the more solid samples of epikarst. Compressive strength results for all samples are given in Table C-4 in Appendix C.

5.2.5 Shear Strength Parameters

Shear strength parameters of friction and cohesion parameters were measured by the direct shear test (Figures 26-28). Two tests were performed on epikarst rock of varying degrees of solutional activity. The more competent epikarst has a friction angle of 20° and a cohesion value of 500 psi (35 kg/cm²) for the more competent epikarst rocks. The highly weathered epikarst has a friction angle of 10° and a cohesion of 225 psi (16 kg/cm²). However, since the test results for the highly weathered epikarst showed a significant amount of scatter, the resulting friction angle and cohesion values are not very reliable. See Figures C-1 and C-2 in Appendix C for shear strength parameter graphs. Average friction angle for dolomite is 50-65° (West, 1995). Epikarst friction is less than 40% of dolomite. Variations in the friction angle and cohesion are attributed to the amount of voids and presence of quartz in each sample as described in the case of unconfined compressive strength.

5.3 Data Analysis

The thickness of the epikarst in the foundation of the dam was determined from borehole data. Based on cross section views of the grout lines, epikarst in the foundation ranges from 0-100 ft (0-30.5 m) thick with an average thickness of around 45 ft (13.7 m). This is typical of epikarst which is commonly 50 ft (15.2 m) thick. An example of a
Figure 25: Random samples of compression tested epikarst showing variable strength of epikarst material. Also see Appendix B: Figures B-4 and B-5.

Figure 26: Direct shear test apparatus.
Figure 27: Sample in direct shear test apparatus before failure.

Figure 28: Sample in direct shear test apparatus after failure.
water testing plot used to help confirm the thickness of epikarst below the dam is shown in Appendix D (Figures D-5 and D-6). The borehole data was also used to determine the RQD of the epikarst. Core photos and borehole logs showing the variability of the epikarst and RQD values are also shown in Appendix D (Figures D-1 – D-4 and D-8).

The RQD value for the epikarst in the dam foundation was 54.3%. An RQD between 50-75% is considered fair rock. The RQD, unconfined compression strength, spacing of joints, the condition of joints and the groundwater conditions were used to determine the rock mass rating according to Bieniawski’s (1973) classification system (Table 2). Table 2 (Bieniawski, 1973) shows each parameter has a range of values with ratings assigned to each range. The ratings for the epikarst are shown on Table 3. The epikarst was found to have a Class No. IV (four) rating which corresponds to poor rock mass with cohesion less than 100-150kPa (14.5-21.75psi) and friction angle between 30°-35°.
Table 2: Rock mass rating classification parameters and ratings (Bieniawski, 1973).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range of values</th>
<th>For this low range - uniaxial compressive test is preferred</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Strength of intact rock material</td>
<td>&gt;10 MPa</td>
<td>4-10 MPa</td>
</tr>
<tr>
<td>Point load strength index</td>
<td>&lt;250 MPa</td>
<td>100-250 MPa</td>
</tr>
<tr>
<td>Uniaxial comp. strength</td>
<td>&lt;50 MPa</td>
<td>&lt;1 MPa</td>
</tr>
<tr>
<td>Rating</td>
<td>15</td>
<td>12</td>
</tr>
<tr>
<td>2 Drill core Quality RQD</td>
<td>90-100%</td>
<td>75-90%</td>
</tr>
<tr>
<td>Rating</td>
<td>20</td>
<td>17</td>
</tr>
<tr>
<td>Spacing of discontinuities</td>
<td>&gt;2 m</td>
<td>0.6-2 m</td>
</tr>
<tr>
<td>Rating</td>
<td>20</td>
<td>15</td>
</tr>
<tr>
<td>4 Condition of discontinuities (See E)</td>
<td>Very rough surfaces</td>
<td>Slightly rough surfaces</td>
</tr>
<tr>
<td>Not continuous</td>
<td>Separation &lt; 1 mm</td>
<td>Separation &lt; 1 mm</td>
</tr>
<tr>
<td>Unweathered wall rock</td>
<td>Slightly weathered walls</td>
<td>Highly weathered walls</td>
</tr>
<tr>
<td>Rating</td>
<td>30</td>
<td>25</td>
</tr>
<tr>
<td>Ground water flow per 100 m tunnel length</td>
<td>None</td>
<td>&lt;10</td>
</tr>
<tr>
<td>(Major principal)</td>
<td>0</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>General conditions</td>
<td>Compeletly dry</td>
<td>Damp</td>
</tr>
<tr>
<td>Rating</td>
<td>15</td>
<td>10</td>
</tr>
<tr>
<td>B. RATING ADJUSTMENT FOR DISCONTINUITY ORIENTATIONS (See F)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Strike and dip orientations</td>
<td>Very favourable</td>
<td>Favourable</td>
</tr>
<tr>
<td>Ratings</td>
<td>Tunnels &amp; mines</td>
<td>0</td>
</tr>
<tr>
<td>Foundations</td>
<td>0</td>
<td>-2</td>
</tr>
<tr>
<td>Slopes</td>
<td>0</td>
<td>-5</td>
</tr>
<tr>
<td>C. ROCK MASS CLASSES DETERMINED FROM TOTAL RATINGS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rating</td>
<td>100 = 81</td>
<td>80 = 61</td>
</tr>
<tr>
<td>Class number</td>
<td>1</td>
<td>II</td>
</tr>
<tr>
<td>Description</td>
<td>Very good rock</td>
<td>Good rock</td>
</tr>
<tr>
<td>D. MEANING OF ROCK CLASSES</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Class number</td>
<td>1</td>
<td>II</td>
</tr>
<tr>
<td>Average stand-up time</td>
<td>20 yrs for 15 m span</td>
<td>1 year for 10 m span</td>
</tr>
<tr>
<td>Cohesion of rock mass (kPa)</td>
<td>&gt;400</td>
<td>300-400</td>
</tr>
<tr>
<td>Friction angle of rock mass (deg)</td>
<td>&gt;45</td>
<td>35-45</td>
</tr>
<tr>
<td>E. GUIDELINES FOR CLASSIFICATION OF DISCONTINUITY conditions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Discontinuity length (perpendicular)</td>
<td>&lt; 1 m</td>
<td>1-3 m</td>
</tr>
<tr>
<td>Rating</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td>Separation (spatial)</td>
<td>None</td>
<td>&lt;0.1 mm</td>
</tr>
<tr>
<td>Rating</td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td>Roughness Rating</td>
<td>Very rough</td>
<td>Rough</td>
</tr>
<tr>
<td>Infilling (gouge)</td>
<td>None</td>
<td>Hard infilling</td>
</tr>
<tr>
<td>Rating</td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td>Weathering</td>
<td>Unweathered</td>
<td>Slightly weathered</td>
</tr>
<tr>
<td>Ratings</td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td>F. EFFECT OF DISCONTINUITY STRIKE AND DIP ORIENTATION IN TUNNELLING**</td>
<td>Strike perpendicular to tunnel axis</td>
<td>Strike parallel to tunnel axis</td>
</tr>
<tr>
<td>Drive with dip-Dip 45-90°</td>
<td>Drive with dip-Dip 20-45°</td>
<td>Dip 45-90°</td>
</tr>
<tr>
<td>Very favourable</td>
<td>Favourable</td>
<td>Very favourable</td>
</tr>
<tr>
<td>Drive against dip-Dip 45-90°</td>
<td>Drive against dip-Dip 20-45°</td>
<td>Dip 0-20- Irrespective of strike*</td>
</tr>
<tr>
<td>Fair</td>
<td>Unfavourable</td>
<td>Fair</td>
</tr>
</tbody>
</table>
Table 3: Calculated rock mass rating for the epikarst material.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
<th>Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strength</td>
<td>3-10 MPa</td>
<td>1</td>
</tr>
<tr>
<td>RQD</td>
<td>50%-75%</td>
<td>13</td>
</tr>
<tr>
<td>Spacing of Joints</td>
<td>0.3-1m</td>
<td>20</td>
</tr>
<tr>
<td>Condition of Joints</td>
<td>Open &gt;5mm</td>
<td>0</td>
</tr>
<tr>
<td>Groundwater</td>
<td>Water under mod. Pressure</td>
<td>4</td>
</tr>
<tr>
<td>Orientation of Joints</td>
<td>Unfavorable</td>
<td>-15</td>
</tr>
<tr>
<td>Total Rating</td>
<td></td>
<td>23</td>
</tr>
<tr>
<td>Class Number</td>
<td></td>
<td>IV</td>
</tr>
<tr>
<td>Description</td>
<td></td>
<td>Poor Rock</td>
</tr>
</tbody>
</table>
CHAPTER 6

CURRENT REMEDIAL MEASURES

6.1 Seepage History

Seepage has been visible at higher pools since the dam’s first filling. Before drainage systems were installed in 1972 and 1980, seepage could be seen once the pool reached elevations 515-520. As the pool rose, the entire downstream area, especially near the left abutment, would become wet. French drains were installed in 1972 and 1980 along the base of the left abutment and in the downstream wet areas. After 1980, the downstream area did not become wet until pool elevations reached 525-530. In 1988, an impervious clay seepage blanket was constructed on the upstream slope and upstream left abutment, creating a berm at El. 575. However, the blanket may not be continuous between the embankment slope and the left abutment. Initially, the blanket kept the downstream area dry until the pool reached El. 545. Currently, seepage through the left abutment appears to be increasing each time the pool rises above El. 520. Until the remedial measures are complete, the pool is restricted to El. 494 in the winter, El. 498 in the summer, and below El. 545 during flood events.

After discovery of the sinkhole on the upstream face in 2003, the Kansas Geological Survey (KGS) performed seismic surface wave analysis and the Bureau of Reclamation performed crosshole shear-wave surveys. Both investigations found loose low density material of reduced strength under the dam just above the top of rock,
extending to the right and left of the sinkhole. These investigations determined that the sinkhole most likely formed by internal erosion as material was washed into one of the near-by solution features located in the epikarst foundation (Figure 29). It was decided that a grout curtain be installed before a more permanent cutoff wall was constructed. In the fall of 2003, the grouting contract was awarded to Advanced Construction Techniques, LTD (ACT)/Gannett Fleming, Inc. to grout the foundation epikarst rock immediately downstream and 100 ft (30.5 m) on either side of the sinkhole. During grouting, a solution feature 15 ft (4.6 m) wide and 120 ft (36.6 m) deep was discovered in the foundation rock. It was located 25 ft (7.6 m) below the core of the dam, directly underneath the sinkhole and appeared to be filled with alluvial and residual clays. The sinkhole remediation project was adjusted to grouting two lines (one five feet upstream from the original grout line and one five feet downstream) to build bulkheads (a plug of grout in an open cavity) in the solution feature to prevent the flow of water under the core trench.

The cutoff wall project was divided into two phases. Phase I consisted of exploratory drilling and grouting, and was later expanded to include completion to the major grouting (Clearwater Major Rehab Phase Ib – Completion of Exploratory Drilling and Grouting). ACT/Gannett Fleming was awarded Phase I contract in 2006 and Phase Ib in 2007. Phase II consisted of the cutoff wall construction (Harris, 2007). Bencor-Recon Joint Venture was awarded the Phase II cutoff wall contract in 2008 (U.S. Army Corps of Engineers Little Rock District, 2008) and the wall was recently completed in December of 2012.
Figure 29: Location of sinkhole and the underlying solution features in plan and profile views (Bradley et al., 2008).
6.2 Remediation Process

All construction was performed on a work platform on the upstream side of the dam at elevation 576 (Figure 30). Remediation began by grouting two lines (Phase Ib), the A-line was upstream of the proposed cutoff wall and B-line was downstream of the proposed cutoff wall. Both lines consisted of primary and secondary holes. Primary holes were spaced 20 ft (6 m) apart, then the distance was split-spaced with secondary holes placed between the primary holes [10 ft (3 m) separating the secondary from the primary holes]. In order to intercept all solution cavities and fractures within the epikarst, the holes were angled 15° from vertical. A-line holes dipped toward the left abutment and B-line holes dipped toward the right abutment (Figure 31 and 32). Each hole was drilled in 10 ft (3 m) stages to be water tested then down-staged grouted. Gannett Fleming, Inc. used the Intelligrout System to monitor the grouting process across the dam. After a stage was drilled and a packer was inflated in a hole, the pressure, Lugeon (Lu), and flow rate of water that was pumped in each hole were recorded for five minutes to determine the untreated permeability of the epikarst. The permeability used in this study was obtained from these tests. The process was then repeated with grout. Once a stage was grouted to refusal (the hole stopped taking grout, Lu=0), the grout was allowed to harden, the hole was cleaned, and ready to drill the next 10 ft (3 m) stage for permeability testing and grouting. The holes were drilled, water tested, and grouted to about a depth of 260 ft (79.2 m) below the work platform (Knight & Hockenberry, 2008). Average grout take per 10 ft (3m) stage was 277 gallons for primary holes, 258 gallons in secondary holes and 45 gallons in tertiary holes. Once all holes were grouted to their
specified depths, construction of the cutoff wall began. The cutoff wall was constructed by milling out 10 ft by 3 ft (3m by 0.9m) panels between the grout lines with a hydromill (Figure D-7). After three consecutive panels were excavated, the space was filled with concrete. Panels were overlapped until a continuous wall was constructed across the length of the dam (US Army Corps of Engineers Little Rock District, 2008).

This research was performed concurrently with the construction of the cutoff wall and was not complete until the cutoff wall was installed. As a result, the conclusions determined from this study were not used by the USACE or Gannett Fleming to refine their construction methods. The results of this research would not likely have altered the decisions previously made as the method of excavation and the extent of the cutoff wall were adequate for the conditions found at the site. While this research was not directly applied to the rehabilitation of this dam, it is still significant work. Many dams across the country are founded on karstic rock but there has been little study of epikarst to date. The analysis of epikarst engineering properties can be applied to other projects founded on epikarst material which are being evaluated to undergo remediation in the future in order to successfully design an appropriate foundation treatment.
Figure 30: View of work platform from right abutment. A-line and B-line production holes can be seen.
Figure 31: Rotary drilling angled grout hole on the B-Line.
Figure 32: Work platform showing angle of A-Line and B-Line holes.
SUMMARY OF FINDINGS

The epikarst at the Clearwater Dam site is a highly variable zone created by the weathering and solution of the Potosi dolomite along joints. The zone spans up to 100 ft (30.5 m) in the foundation of the dam. Upstream, the epikarst is exposed in an outcrop where it formed along the bedding planes, joints and top surface of the Potosi dolomite (Figure 33). Here, the thickness of epikarst spans the entire outcrop of approximately 30 ft (9.1 m) before it reaches the lake. The presence of epikarst and joints create serious seepage and piping problems in the dam. The dam has recently undergone remediation to install a cutoff wall through the dam to block the flow of water through the unfiltered cavities which are present in the epikarstic foundation of the dam.

Investigations of the epikarst from the “Epikarst Beach” site upstream of the dam have provided a better understanding of the properties of epikarst. Joint measurements from this site, as well as those done by Gannett Fleming, Inc. on the right abutment, show two major joint sets spanning from a mile upstream in Clearwater Lake to the downstream right abutment. Solution features below the dam have similar trends. The joints at this site are closely spaced, with a continuity of 3.25 ft (1 m) and an average aperture of 1 inch (2.5 cm). This regional jointing is both a cause of the seepage and for the continuation of epikarst development by the easy flow of water through the ever widening joints and cavities. The close proximity to the Reelfoot Rift suggests that the
area is still experiencing tectonic stresses, creating more joints and fractures, which can lead to more epikarst formation (George, 2007).

Laboratory testing revealed a much weaker and more porous rock than typical dolomite. Epikarst porosity is roughly 50%, specific gravity is nearly half of typical dolomite, and absorption is twice that of dolomite. These three properties show the decrease of rock mass and the increase of void space. This allows for a weaker rock and the increased presence of water, which continues epikarst formation. The unconfined compressive strength and shear strength parameters were significantly lower than dolomite, proving the epikarst is at least 50% weaker. However, there was some variation of strength between different samples (Figure 34). These variations can be attributed to the degree of vugginess and amount of quartz in the samples. Epikarst does not form evenly across an area. Where joints are more closely spaced and water is concentrated, epikarst develops better. Also, the Potosi dolomite contains quartz which is not evenly distributed across the formation. Samples which contain more advanced epikarst and little to no quartz have lower strengths. Samples with more quartz are less soluble, leading to higher strengths when tested. As noted in chapter 5, even though one of the direct shear tests was performed on samples with more quartz and less developed epikarst, it still had significantly lower strength parameters than average dolomite. Borehole images, shown in Appendix D, help show the variability in the epikarst.

The epikarst at Clearwater Dam is a very weak rock. The RQD and RMR determined by field observations classify the rock as fair to poor, respectively. Epikarst is formed through the dissolution of the Potosi dolomite along regional joint sets that run
through the foundation of the dam. While epikarst formation is extensive at the site, it is not evenly distributed. Formation depends on several factors and can vary a few feet away. With the completion of a cutoff wall, seepage through the dam foundation will be reduced. However, epikarst development can continue and eventually create new seepage paths, which in turn, will need to be treated.
Figure 33: A close-up of epikarst outcrop.

Figure 34: Two epikarst samples demonstrating different compressive strengths.
REFERENCES


Kisvarsanyi, E. B., 1984, Structural Map of the Precambrian Surface in Missouri, Missouri Geological Survey, Open File Map OFM-84-207-GI.


Missouri Department of Natural Resources, 1995, *Shaded Relief Map of Missouri (With Physiographic Divisions and Large Springs)*. Rolla, Missouri.


U.S. Army Corps of Engineers, Little Rock District, 1989, Clearwater Dam Grouting Completion Report, Right Abutment Sta. 53+00 to 56+55.


APPENDIX A

DAM PHOTOGRAPHS
Figure A-1: Dam site before construction (USACE-a, 2010).
Figure A-2: Excavation of cutoff trench (USACE-a, 2010).
Figure A-3: Open joint located in the cutoff trench foundation (USACE-a, 2010).
Figure A-4: View from right abutment of impervious clay core and embankment fill (USACE-a, 2010).
Figure A-5: View from left abutment of impervious clay core and embankment fill (USACE-a, 2010).
Figure A-7: Original cross section of Clearwater Dam (Bradley et al., 2008).
Figure A-8: Current cross section of Clearwater Dam (Bradley et al., 2008).
APPENDIX B

SAMPLE PHOTOGRAPHS
Figure B-1: Field site showing epikarst in thick layers at the top of the approximate 15 ft (4.6 m) high outcrop.
Figure B-2: Field site showing epikarst formation at the top of the outcrop and along horizontal bedding planes.
Figure B-3: Typical detailed line survey on epikarst outcrop.
Figure B-4: Random samples of compression tested epikarst with lower compressive strength.

Figure B-5: Random samples of compression tested epikarst with greater compressive strength.
APPENDIX C

LABORATORY TEST RESULTS
Table C-1: Absorption test results.

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Sat. Wt (g)</th>
<th>Dry Wt (g)</th>
<th>ABSORPTION (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>152.4</td>
<td>133.6</td>
<td>14.1</td>
</tr>
<tr>
<td>2</td>
<td>83</td>
<td>72.2</td>
<td>15</td>
</tr>
<tr>
<td>3</td>
<td>115.6</td>
<td>102.6</td>
<td>12.6</td>
</tr>
<tr>
<td>4</td>
<td>101.3</td>
<td>92.7</td>
<td>9.3</td>
</tr>
<tr>
<td>5</td>
<td>136.3</td>
<td>127.5</td>
<td>6.9</td>
</tr>
<tr>
<td>6</td>
<td>140.2</td>
<td>123.8</td>
<td>12.2</td>
</tr>
<tr>
<td>7</td>
<td>102</td>
<td>95.8</td>
<td>6.4</td>
</tr>
<tr>
<td>8</td>
<td>139.5</td>
<td>126.8</td>
<td>10</td>
</tr>
<tr>
<td>9</td>
<td>154.2</td>
<td>139.2</td>
<td>10.8</td>
</tr>
<tr>
<td>10</td>
<td>101.6</td>
<td>91</td>
<td>11.6</td>
</tr>
<tr>
<td>11</td>
<td>161.9</td>
<td>146.3</td>
<td>10.7</td>
</tr>
<tr>
<td>12</td>
<td>173.3</td>
<td>151.4</td>
<td>14.5</td>
</tr>
<tr>
<td>13</td>
<td>130.2</td>
<td>118.2</td>
<td>10.2</td>
</tr>
<tr>
<td>14</td>
<td>86.1</td>
<td>81.2</td>
<td>6</td>
</tr>
<tr>
<td>15</td>
<td>159</td>
<td>140.5</td>
<td>13.2</td>
</tr>
</tbody>
</table>

Average Absorption 10.9
Standard Deviation 2.9
Table C-2: Results of Specific Gravity Testing.

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Sub. Wt (g)</th>
<th>Volume</th>
<th>Specific Gravity</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>47.5</td>
<td>54.5</td>
<td>1.8</td>
</tr>
<tr>
<td>8</td>
<td>66.5</td>
<td>73</td>
<td>1.7</td>
</tr>
<tr>
<td>9</td>
<td>70.4</td>
<td>83.8</td>
<td>1.7</td>
</tr>
<tr>
<td>10</td>
<td>49</td>
<td>52.6</td>
<td>1.7</td>
</tr>
<tr>
<td>11</td>
<td>70.7</td>
<td>91.2</td>
<td>1.6</td>
</tr>
<tr>
<td>12</td>
<td>79.6</td>
<td>93.7</td>
<td>1.6</td>
</tr>
<tr>
<td>13</td>
<td>66.1</td>
<td>64.1</td>
<td>1.8</td>
</tr>
<tr>
<td>14</td>
<td>44.6</td>
<td>41.5</td>
<td>2.0</td>
</tr>
<tr>
<td>15</td>
<td>72.5</td>
<td>86.5</td>
<td>1.6</td>
</tr>
</tbody>
</table>

Average Specific Gravity: 1.7
Standard Deviation: 0.12

Table C-3: Results of porosity calculations.

<table>
<thead>
<tr>
<th>Sample</th>
<th>% Porosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>50.4</td>
</tr>
<tr>
<td>8</td>
<td>47.6</td>
</tr>
<tr>
<td>9</td>
<td>49.4</td>
</tr>
<tr>
<td>10</td>
<td>46.2</td>
</tr>
<tr>
<td>11</td>
<td>51.5</td>
</tr>
<tr>
<td>12</td>
<td>47.6</td>
</tr>
<tr>
<td>13</td>
<td>44</td>
</tr>
<tr>
<td>14</td>
<td>45.2</td>
</tr>
<tr>
<td>15</td>
<td>48.3</td>
</tr>
</tbody>
</table>

Average: 47.8
Standard Dev. 2.4
Table C-4: Results of unconfined compressive strength.

<table>
<thead>
<tr>
<th>Cube sample Number</th>
<th>Load (kg)</th>
<th>Rate (kg/min)</th>
<th>Strength (kg/cm²)</th>
<th>Adjusted Strength (kg/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>206</td>
<td>38</td>
<td>13</td>
<td>11</td>
</tr>
<tr>
<td>2</td>
<td>2646</td>
<td>176</td>
<td>100</td>
<td>85</td>
</tr>
<tr>
<td>3</td>
<td>431</td>
<td>66</td>
<td>16</td>
<td>13.6</td>
</tr>
<tr>
<td>4</td>
<td>843</td>
<td>141</td>
<td>30</td>
<td>25.5</td>
</tr>
<tr>
<td>5</td>
<td>897</td>
<td>128</td>
<td>42</td>
<td>35.7</td>
</tr>
<tr>
<td>6</td>
<td>592</td>
<td>85</td>
<td>30</td>
<td>25.5</td>
</tr>
<tr>
<td>7</td>
<td>682</td>
<td>76</td>
<td>34</td>
<td>28.9</td>
</tr>
<tr>
<td>8</td>
<td>1399</td>
<td>187</td>
<td>60</td>
<td>51</td>
</tr>
<tr>
<td>9</td>
<td>655</td>
<td>87</td>
<td>40</td>
<td>34</td>
</tr>
<tr>
<td>10</td>
<td>987</td>
<td>90</td>
<td>39</td>
<td>33.2</td>
</tr>
<tr>
<td>11</td>
<td>457</td>
<td>42</td>
<td>19</td>
<td>16.2</td>
</tr>
<tr>
<td>12</td>
<td>484</td>
<td>81</td>
<td>33</td>
<td>28</td>
</tr>
<tr>
<td>13</td>
<td>1103</td>
<td>147</td>
<td>57</td>
<td>48.5</td>
</tr>
<tr>
<td>14</td>
<td>1426</td>
<td>130</td>
<td>71</td>
<td>60.4</td>
</tr>
<tr>
<td>15</td>
<td>2879</td>
<td>262</td>
<td>175</td>
<td>148.8</td>
</tr>
<tr>
<td>16</td>
<td>2736</td>
<td>322</td>
<td>159</td>
<td>135.2</td>
</tr>
<tr>
<td>17</td>
<td>350</td>
<td>70</td>
<td>25</td>
<td>21.3</td>
</tr>
<tr>
<td>18</td>
<td>1372</td>
<td>125</td>
<td>59</td>
<td>50.2</td>
</tr>
<tr>
<td>19</td>
<td>816</td>
<td>82</td>
<td>70</td>
<td>59.5</td>
</tr>
<tr>
<td>20</td>
<td>431</td>
<td>86</td>
<td>25</td>
<td>21.3</td>
</tr>
<tr>
<td>Average Unconfined Compressive Strength</td>
<td>55 (780 psi)</td>
<td>46.6 (661 psi)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>44 (624psi)</td>
<td>37.5 (532 psi)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure C-1: Direct shear results for more weathered epikarst, cohesion=225 psi, friction angle = 10°.

Figure C-2: Direct shear results for more competent epikarst, cohesion=500 psi, friction angle = 20°.
APPENDIX D

BOREHOLE PHOTOGRAPHS AND DATA
Figure D-1: Rock core taken from EP18, depth 74.7’, elevation 503.8’, Lugeon = 218 showing highly weathered epikarst with quartz (Knight & Hockenberry, 2008).
Figure D-2: Rock core taken from EP19, depth 133.6’, elevation 447’, Lugeon = 55 with near vertical fracture (Knight & Hockenberry, 2008).
Figure D-3: Rock core taken from EP19, depth 226.2’, elevation 357.5’, Lugeon = 250 with some quartz filled voids (Knight & Hockenberry, 2008).
Figure D-4: Mottled dolomite rock core taken from EP19, depth 152’, elevation 429.2’, Lugeon = 15 (Knight & Hockenberry, 2008).
Figure D-5: Section along A-line showing results of water testing and used to determine epikarst thickness below the dam (Knight and Hockenberry, 2008). See Figure D-6 for legend.
Figure D-6: Legend for A-line water testing section in Figure D-5 (Knight and Hockenberry, 2008).
Figure D-7: Hydromill used to excavate the cutoff wall.
Figure D-8: Drilling log showing cavities and fractured nature of the epikarst below Clearwater Dam.
Figure D-8 continued.
Figure D-8 continued.
Figure D-8 continued.
Figure D-8 continued.
Figure D-8 continued.
Figure D-8 continued.
Figure D-8 continued.

<table>
<thead>
<tr>
<th>ELEVATION</th>
<th>DEPTH</th>
<th>LEGEND</th>
<th>CLASSIFICATION OF MATERIALS (Description)</th>
<th>% CORE</th>
<th>REMARKS</th>
</tr>
</thead>
<tbody>
<tr>
<td>248</td>
<td>248.0</td>
<td></td>
<td>247.1' - 248.0': Intersecting high angle joints, broken</td>
<td>248</td>
<td></td>
</tr>
<tr>
<td>248.0</td>
<td>248.3</td>
<td></td>
<td>248.6' - 248.3': Parallel high angle joints (57'), RD=70'</td>
<td>248</td>
<td></td>
</tr>
<tr>
<td>249.2</td>
<td>248.9</td>
<td></td>
<td>248.2' - 248.9': Calcite lined vugs, open</td>
<td>248</td>
<td></td>
</tr>
<tr>
<td>250</td>
<td>250.0</td>
<td></td>
<td></td>
<td>250</td>
<td></td>
</tr>
<tr>
<td>252.5</td>
<td>252.5</td>
<td></td>
<td>252.5' - 253.5': High angle joint, RD=70'</td>
<td>252</td>
<td></td>
</tr>
<tr>
<td>254</td>
<td>254.0</td>
<td></td>
<td>254.0' - 257.7': Broken to very broken, clay and sand, drilling present</td>
<td>254</td>
<td></td>
</tr>
<tr>
<td>328.1</td>
<td>328.1</td>
<td></td>
<td>Bottom of Boring = 257.7 ft.</td>
<td>254</td>
<td></td>
</tr>
</tbody>
</table>