Geologic stability of Mystic Lake dam, Gallatin County, Montana, and computer simulation of potential flood hazards from the failure of the dam
by Graham Stephen Hayes

A thesis submitted in partial fuIIfiIlment of the requirements for the degree of MASTER OF SCIENCE i n Earth Science
Montana State University

Abstract:
The failure of Mystic Lake dam poses a major threat to the residents of the Bozeman Creek drainage. Outdated engineering practices used in the construction of the dam coupled with an unstable geologic setting create a potentially hazardous situation. The east abutment of the oam is founded in the toe of a Quaternary landslide. Water seeps through the landslide debris and ponds in a depression at the foot of the dam. Unvegetated slumo scarps in the landslide directly below the dam site are attributed to the increased pore pressure from the seepage water. The potential for liquefaction in the event of an earthquake is extrerne Iy high.

A mathematical model is programmed in FORTRAN IV to simulate the failure of the dam and the movement of the floodwave. The hypothetical failure is induced by overtopping the dam with a rain-storm discharge greater than the spillway capacity (780 cfs). The breach is assumed to erode as an exponential function of time, producing an estimated peak discharge of 83,500 cfs in approximately 7.5 minutes.

A hydraulic routing method utilizing the complete equations of unsteady flow is solved numerically by a four-point implicit finite difference method.

Changes in the flow regime of Bozeman Creek make the computation of the initial water surface profile and the establishment of intermediate boundary conditions impossible. Until sufficient gaging data are available# trie routing portion of the model is not applicable to Bozeman Creek and the extent of flooding from the failure of Mystic Lake dam cannot be simulated.

An estimate for the extent of flooding from the failure of the dam is approximated by plotting the percentage attenuation of the breach hydrograph against the depth of flow.

A 60 percent attenuation yields a depth' of flow of 10.5 feet, at the canyon mouth # 4.5 feet deeper than the 5 CO year flood.

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of

MASTER OF SCIENCE

in

Earth Science

Approved:

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MONTANA STATE UNIVERSITY
Bozeman, Montana

April, 1981

VITA

Graham Stephen Hayes was born in Chatham, Ontario, Canada on December 28, 1955. His parents are Wilfred H. Hayes and Katherine V. Hayes. He graduated from Cypress Lake Senior High School, Fort Myers, Florida, in June 1973. He received a Bachelor of Science degree in geology from Wheaton College, Wheaton, Illinois, in June 1977. After working one summer for the Geological Survey of Canada, he married Karen S. Markello on June 17, 1978. He entered the graduate school at Montana State University the following September, and held both research and teaching assitantships while working toward a Master of Science Degree in Earth Sciences.

ACKNOWLEDGMENT

The author wishes to extend his thanks to Dr. Stephan Custer (committee chairman), and Dr. Donald L. Smith (reading committee), for initiating the study and providing continual encouragement and help throughout the investigation. Special thanks to Dr. Michael Amein, Univ. of North Carolina Raleigh, for his helpful correspondence and program listings. My appreciation to Professor Martin Faulkner and Dr. Del Dyreson (reading committee), and to Mark Hinrichs and Georgia Ziemba for their invaluable help with the programming aspect of the thesis.

The writer is also indebted to Mr. Norm Buhl, of the U.S. Forest Service, for allowing vehicle access to the dam site; to Mr. Ralph Bergantine, of the U.S. Soil Conservation Service, for providing stream cross-section data; to Professor Robert Taylor and Glen Wyatt for their advice concerning drafting problems; and to Tom Grady for the countless hours of discussion and head-scratching concerning the equations of unsteady flow.

Finally, a note of thanks to my wife Karen, for her constant support, patience with my long and late hours on the computer, and for typing the final copy of the thesis.

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ABSTRACT

The failure of Mystic Lake dam poses a major threat to the residents of the Bozeman Creek drainage. Outdated engineering practices used in the construction of the dam coupled with an unstable geologic setting create a potentially hazardous situation. The east abutment of the dam is founded in the toe of a Quaternary landslide. Water seeps through the landslide debris and ponds in a depression at the foot of the dam. Unvegetated slump scarps in the landslide directly below the dam site are attributed to the increased pore pressure from the seepage water. The potential for liquefaction in the event of an earthquake is extremely high.

A mathematical model is programmed in FORTRAN IV to simulate the failure of the dam and the movement of the floodwave. The hypothetical failure is induced by overtopping the dam with a rain-storm discharge greater than the spillway capacity (780 cfs). The breach is assumed to erode as an exponential function of time, producing an estimated peak discharge of 83,500 cfs in approximately 7.5 minutes. A hydraulic routing method utilizing the complete equations of unsteady flow is solved numerically by a four-point implicit finite difference method.

Changes in the flow regime of Bozeman Creek make the computation of the initial water surface profile and the establishment of intermediate boundary conditions impossible. Until sufficient gaging data are available, the routing portion of the model is not applicable to Bozeman Creek and the extent of flooding from the failure of Mystic Lake dam cannot be simulated.

An estimate for the extent of flooding from the failure of the dam is approximated by plotting the percentage attenuation of the breach hydrograph against the depth of flow. A 60 percent attenuation yields a depth of flow of 10.5 feet at the canyon mouth, 4.5 feet deeper than the 500 year flood.

INTRODUCTION

Location

Bozeman Creek drains 52.4 square miles on the northern flanks of the Gallatin Range, southwestern Montana. The upper 4.9 square miles of the drainage basin drain into Mystic Lake (Fig. 1). The lake is 12 miles southeast of Bozeman in the eastern half of section 25, Township 3 South, Range 6 East, and in the western half of section 30, Township 3 South, Range 7 East. From Mystic Lake, Bozeman Creek flows 7 miles through a narrow, forested, northwest-trending canyon (Fig. 1). The lower reach of the stream, between the canyon mouth and the East Gallatin River, occupies a narrow floodplain (less than one mile wide), which is undergoing steady urbanization. Many residential and commercial developments have established on the floodplain including part of downtown Bozeman (Fig. 1).

Purpose of the Study

According to guidelines established by the U.S. Corps of Engineers (1975), Mystic Lake dam is classified as having a high downstream hazard potential. In an executive summary Foster (CH2M Hill, 1980, p. iv) stated:

> Based on visual reconnaissance and engineering judgement, the dam is located such that its failure could cause extensive property damage and possible loss of life.

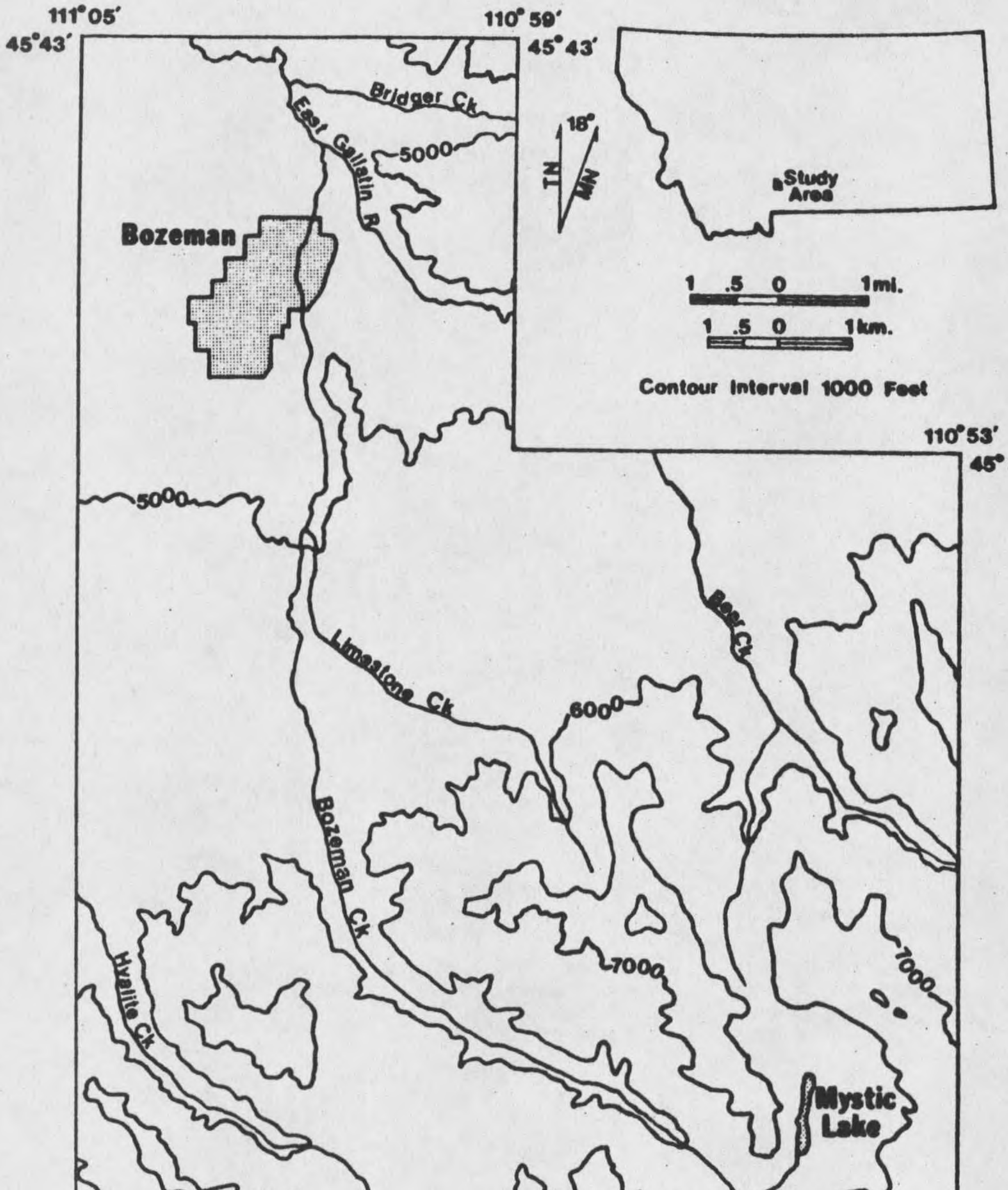


Figure 1. Location map. Note the spatial relationship between Mystic Lake, Bozeman Creek and the town of Bozeman.

In his recommendations to the city of Bozeman, the Bozeman Creek Reservoir Company and the U.S. Corps of Engineers, he stressed the need for further evaluation of the dam's geologic stability and for a hydraulic routing to establish the extent of downstream flooding associated with the failure of the dam.

The purpose of this investigation is twofold: first, to evaluate the stability of Mystic Lake dam by compiling all available engineering data and conducting a geologic investigation of the dam site, and second, to demonstrate the extent of potential flooding along Bozeman Creek by numerically simulating the failure of the dam and the movement of the floodwave downstream.

History of the Dam

The following section was summarized from a report by Bozeman City Engineer, Art Van't Hul (1980).

Mystic Lake dam was constructed in 1903 and 1904 on U.S. Forest Service property through a special use permit granted to the city of Bozeman and the Bozeman Creek Reservoir Company. The lake is used to store irrigation and municipal waters. The original earth-fill structure measured 43 feet in height from the outlet pipes (one 16 and the other 12 inches in diameter), to the dam crest (Fig. 2-A,B). Both

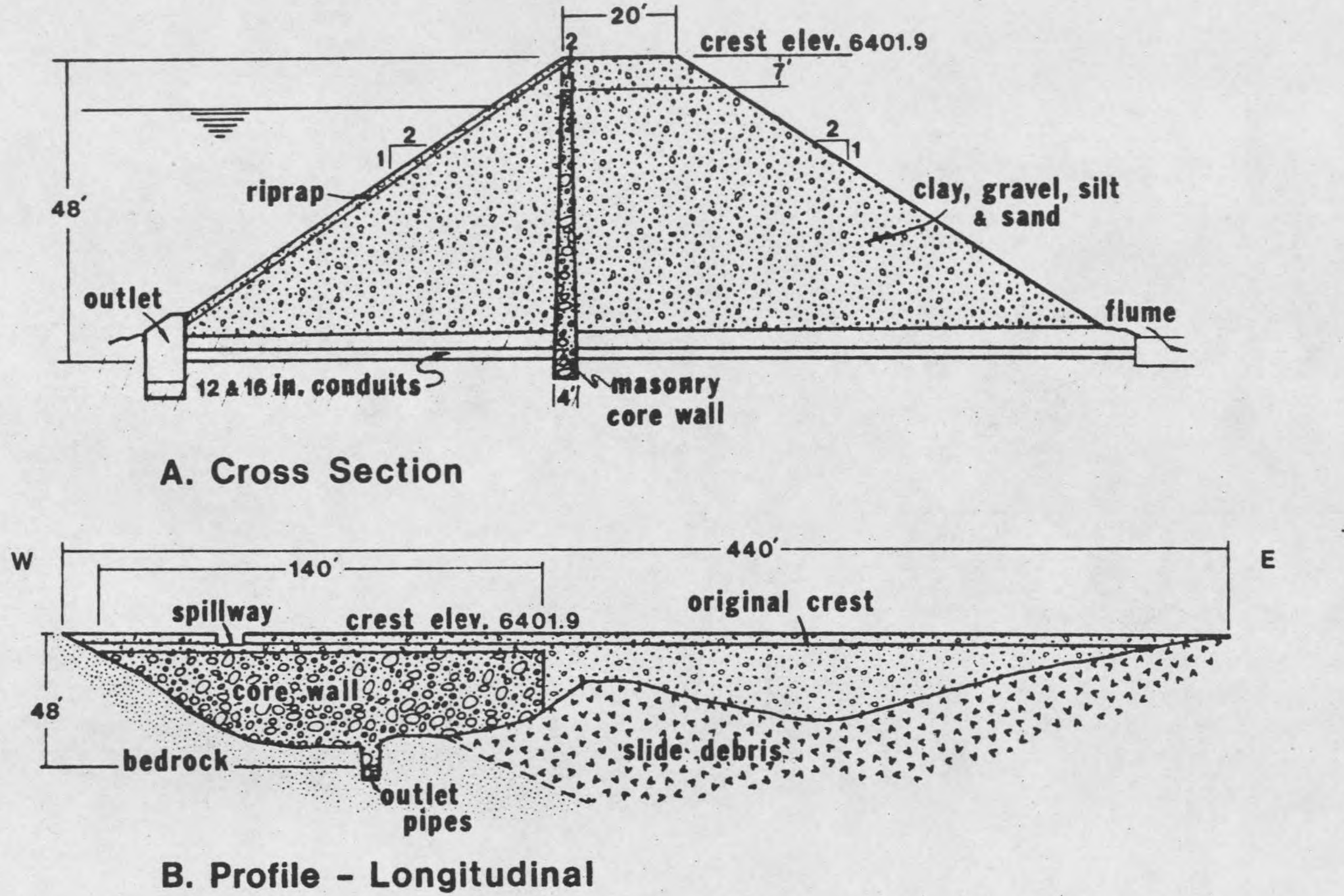
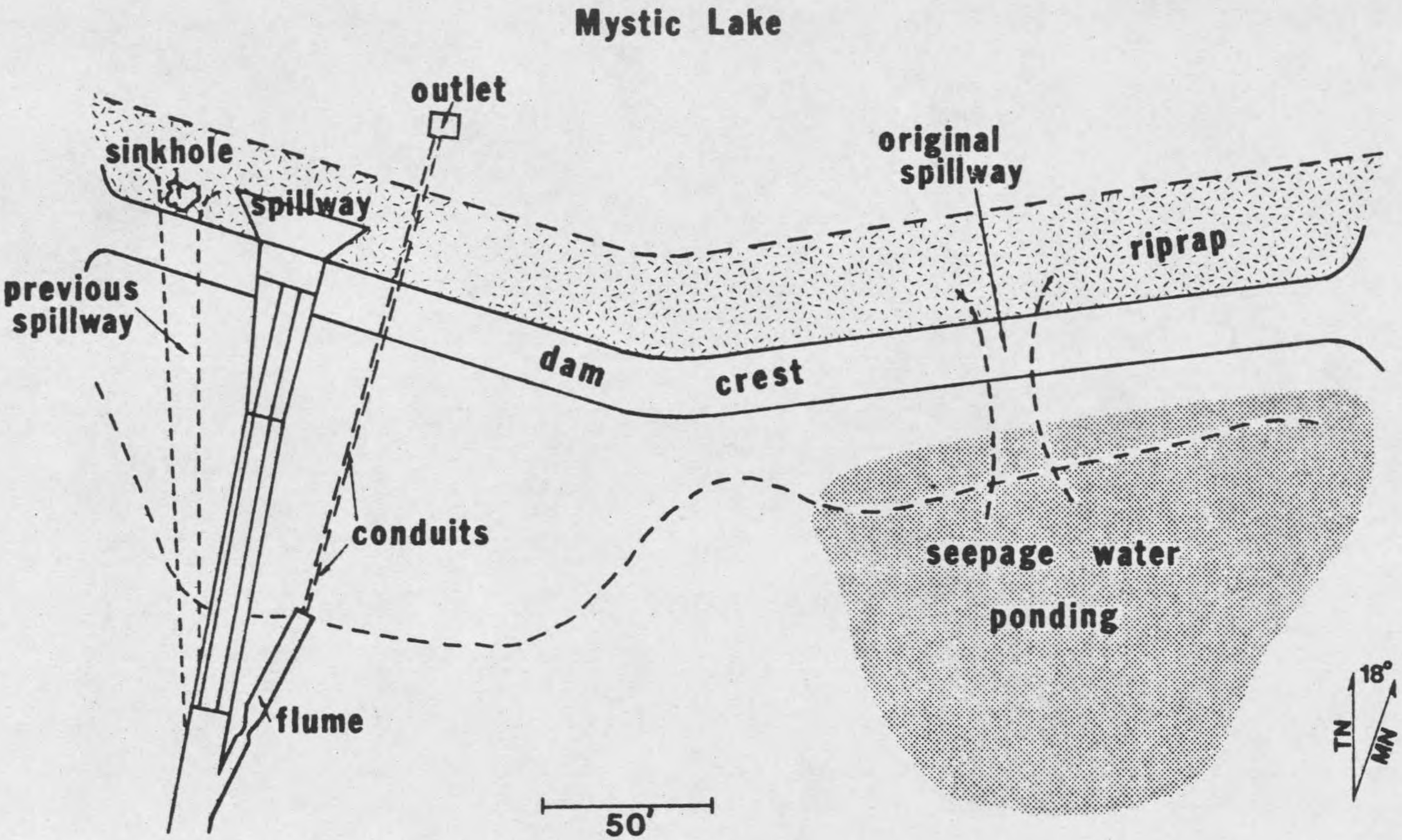


Figure 2. Engineering drawings of Mystic Lake dam. Cross-section A is drawn through the dam along the outlet pipes. Note the extent of the core wall in the longitudinal profile B. Where the core wall is absent, seepage water ponds in a depression at the toe of the dam, plan view C.



C. Plan View

Figure 2. (continued)

upstream and downstream faces had slopes of 2 to 1 with the upstream face riprapped. A masonry core wall, 4 feet thick at the base, 2 feet thick at the top, and 140 feet long, extended from the west abutment through the center line of the dam. The top of the core wall was approximately 2 feet below the original crest of the dam (Fig. 2-A, B).

There have been several modifications to the dam since its installation in 1903. A concrete spillway was constructed in 1919 near the west abutment to replace the original timber spillway (Fig. 2-C). In 1932, a high runoff event leaving only a .9 foot freeboard on the dam, prompted officials to raise the dam crest by 3 feet to the height of the spillway cover slab. In 1959, a new concrete spillway, 185 feet long and 20 feet wide was installed with a Parshall Flume at the outlet pipes (Fig. 2-C). At the same time, the dam crest was raised two feet to its present height of 48 feet. At this new elevation, the 440 foot long dam impounded 1190 acre-feet at the spillway crest, and 1520 acre-feet at the dam crest. In the fall of 1964, the old gate structure was dismantled and a new concrete outlet control with a hand operated slide gate was installed. Three years later, in 1967, a longitudinal crack developed in the lower end of the spillway floor. The repairs were made by injecting a mixture of masonry cement, washed sand, and bentonite into a series of holes drilled through the spillway floor.

In July, 1977, water was observed entering a sinkhole in the upstream face of the dam (Fig. 2-C), accompanied by a loud roar from within the dam. Muddy water and algae were observed issuing from a pool 200 to 300 feet downstream from the end of the spillway. As the reservoir level decreased, the sound from within the dam lessened and the flow of water through the sinkhole diminished (Williams, 1977). Drill hole and fluorescein dye tests conducted by Northern Testing Laboratories (1977), and television monitoring of the outlet pipes by Bozeman city officials in 1977-78, led to the conclusion that differential settlement of the core wall and the dam embankment had sheared the 12 inch outlet pipe. Inspections revealed that the 12 inch diameter pipe had a 3 inch vertical displacement at the upstream face of the core wall, and that both cast iron conduits had long bends and locally out-of-round sections. In order to prevent further removal of material from the dam by piping, and additional sinkhole development, mechanical expanding plugs were inserted into the upstream and downstream ends of the 12 inch outlet pipe as a temporary measure until more complete repairs could be made (Northern Testing Laboratories, 1977).