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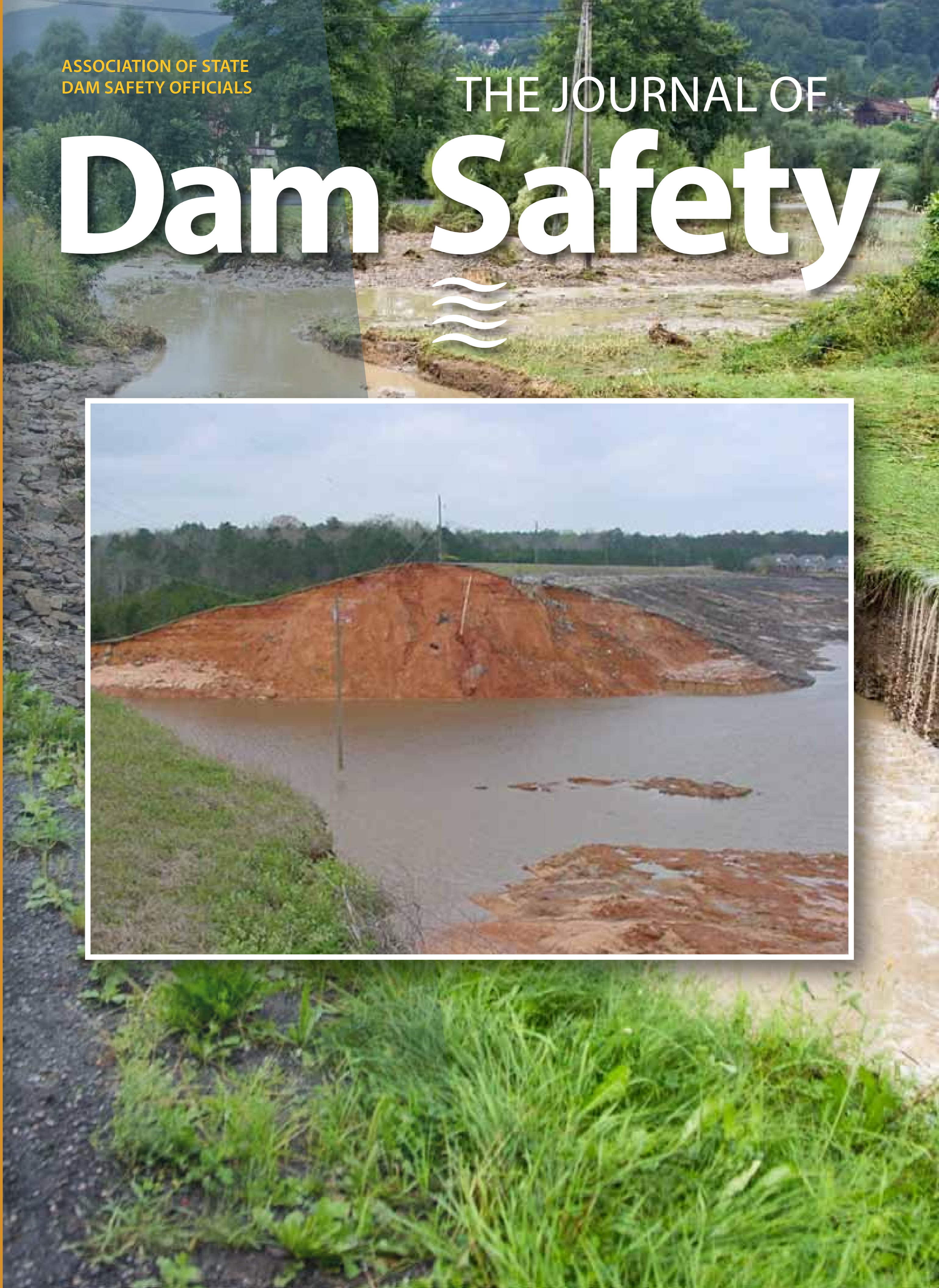

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BIG BAY DAM

REEXAMINATION AND LESSONS LEARNED FROM THE 2004 FAILURE OF BIG BAY DAM, MISSISSIPPI

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INTRODUCTION

Big Bay Dam is a 57' tall, approximately 2000' long, earthen embankment dam located in south central Mississippi (Figure 1). The construction of the dam in 1990-1991 created a 900-acre lake with a storage capacity of more than 11,000 acre-feet, which is primarily used for recreation. The original dam breached on March 12, 2004 due to piping/internal erosion mechanisms that occurred over a period of years. The final stages of the failure took less than 24 hours.

The failure destroyed 48 homes, washed out a bridge, and damaged 53 homes, 2 churches, 3 businesses, and a fire station. Thankfully, no lives were lost. The primary failure investigation report, prepared by the lead engineer for the original design of the dam, concluded that the dam had failed by piping through the foundation.

As a result, many people were led to believe that the dam failed in less than 24 hours by piping through the foundation without any previous signs of distress. This misconception resulted in discussions in late 2012 between the State of Mississippi and the ASDSO Dam Failures and Incidents Committee about how the 'real story' of Big Bay could be determined and how the Committee's 2011 Dam Failure Investigation Guidelines could be tested in the process. The authors then made an extensive effort to investigate the failure, including evaluating all available documentation and performing a visit to the site in 2013. The results of this effort were presented in an in-depth technical paper and presentation which evaluated the failure in a potential failure modes analysis framework. This paper was presented at the 2014 United States Society on Dams Conference. Two additional papers and a Soapbox Session to discuss lessons learned from the failure were presented at the 2014 ASDSO national conference. This article summarizes that work, emphasizing the many distress indicators and other warning signs extending back to the construction of the dam, as well as lessons learned as a culmination to this investigation process.

Big Bay Lake Dam

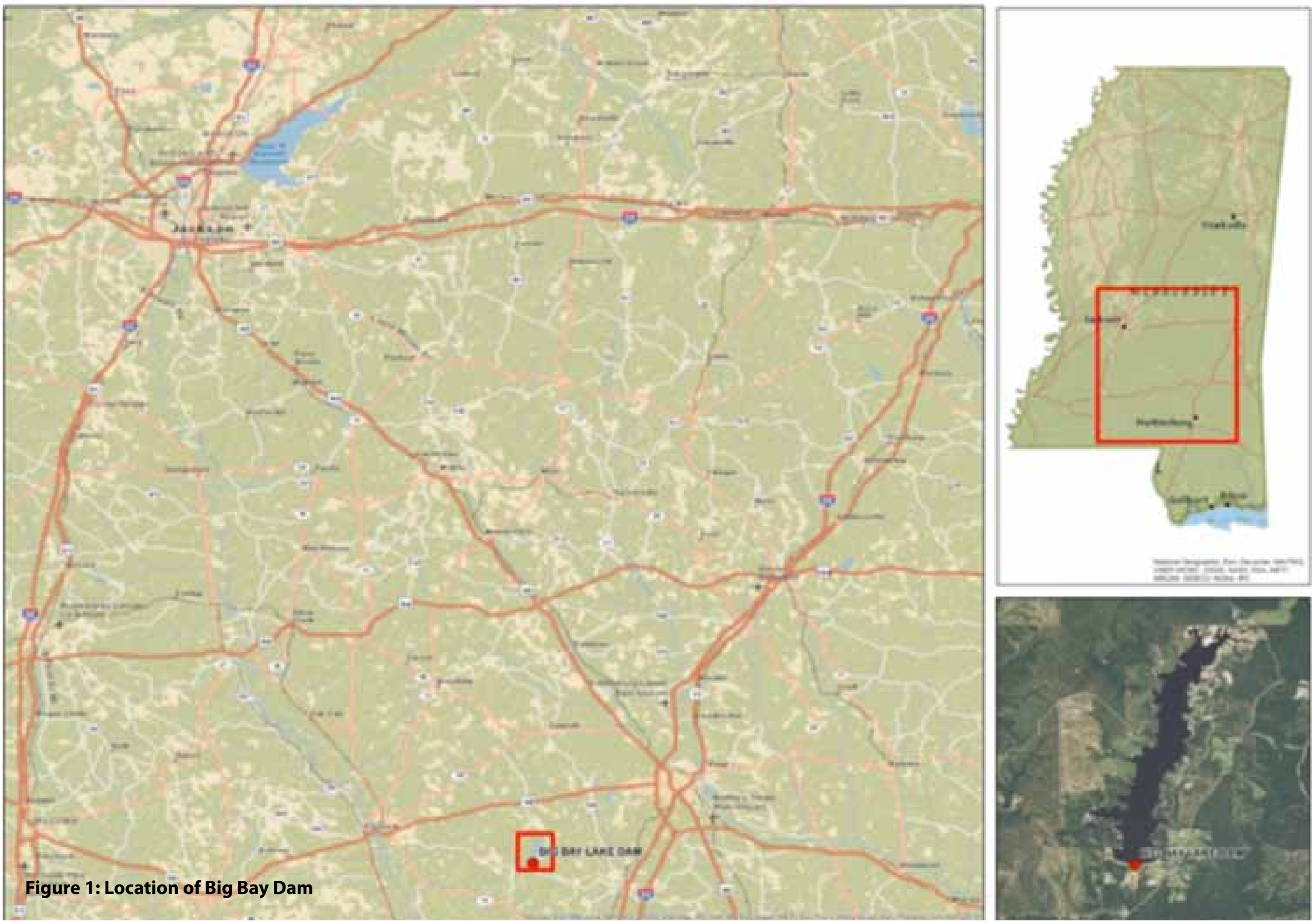

Figure 1: Location of Big Bay Dam

DAM DESCRIPTION, CHRONOLOGY, DISTRESS INDICATORS, AND OTHER WARNING SIGNS

Based on review of voluminous available records (plans, photos, boring logs, soil lab test data, inspection reports, correspondence, depositions, failure investigation reports, etc.), the dam was designed during the mid to late 1980s and constructed in 1990 and 1991. It was an earthen embankment dam approximately 2000' long and 57' high, constructed primarily using silty sand. It was aligned on an east-west axis, with the reservoir to the north (southward flow). The upstream and downstream slopes were 3:1 (horizontal:vertical) with horizontal benches on each face, making the base up to about 360' wide. The design plans called for a uniform and consistent core/cutoff wall constructed of bentonite mixed with the on-site silty sand, 10' to 14' thick, extending a foot above normal pool and down at least 15' into the foundation (the plans are inconsistent regarding this depth). The reservoir filled to normal pool depth by around 1993 and was generally maintained at the full normal pool depth until the time of the failure.

The outlet works consisted of a concrete riser, an 8' x 8' concrete box culvert conduit, a concrete apron and wingwalls at the conduit outlet, and a riprap stilling basin downstream of the apron. Virtually no documentation of the construction and as-built conditions was found in the available records. From the time of first filling of the dam, completed in 1993, until the failure in 2004, the dam exhibited several distress indicators and other warning signs. Substantial leakage into the conduit was observed at multiple locations by the time the reservoir filled, and continued until the dam failed in 2004, with the leakage locations apparently changing over time. Videos from as early as 1995 show substantial leakage into the conduit downstream of the purported core of the dam.

Figure 2: 1995 Leakage into the conduit

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In 1993, a local resident complained that the dam was leaking. The State Dam Safety Program inspected the dam and found "wet spots all along the downstream slope of the dam." The lead design engineer for the original dam prepared remedial plans that called for a toe drain and "installation of relief drains for slope stabilization" at the downstream face of the dam. In 1999, the dam owner observed seepage in the downstream face surrounding the outlet of the conduit. Substantial excavation and backfilling were performed in this area, including use of filter fabric. Plans for this work were not located. It was also noted that a substantial amount of "silt" had accumulated in the stilling basin, which was removed. This work was never reviewed or approved by the State Dam Safety Program, and there is little to no documentation for this remedial work.

By 2002, a "sinkhole" in the downstream slope had been backfilled (Figure 3). The exact location is not known, and plans for this work were not located, but available records suggest that the sinkhole location was most likely directly above the conduit. In August 2002, the Owner sent the Engineer a letter authorizing studying leaks (Figure 4) and performing annual inspections, and indicating that

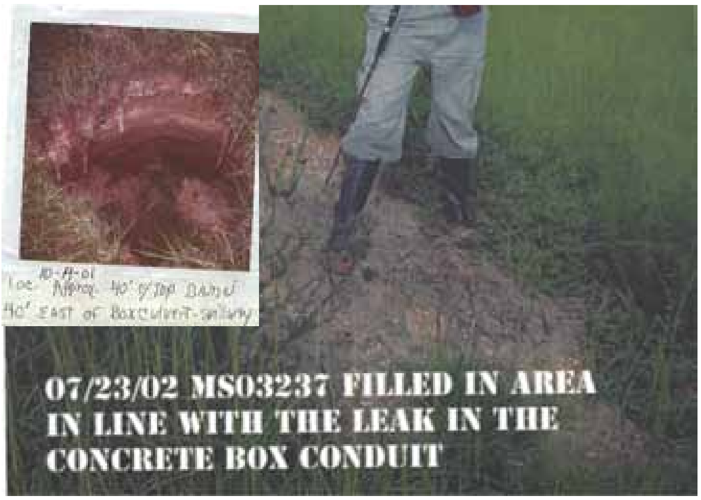

Figure 3: Sinkhole near conduit

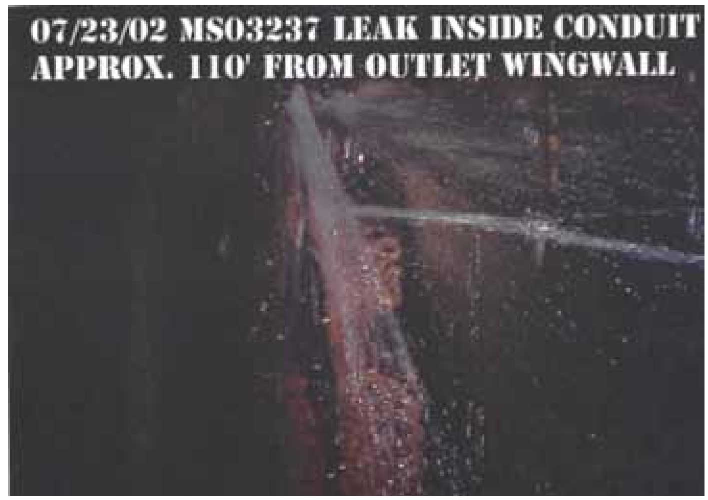

Figure 4: Leakage into the conduit

weekly inspections were being done by the Maintenance Person to look for wet spots, discolored water in the "outflow lagoon," etc.

Finally, there were two eye witnesses to the failure of the dam, including the Owner's Maintenance Person and Engineer. The sequence of events immediately preceding the failure began on Thursday afternoon, March 11, 2004, when the Owner's Maintenance Person was notified by one of the residents in the area that the 6-inch diameter drain pipe discharging from the west side of the outlet works wing wall into the stilling basin was flowing "mud." The date and time of this notification are not clear in the available information, but were likely sometime on the morning or early afternoon of March 11th, the day prior to the failure. This pipe normally did not flow water other than during periods immediately following significant rain. The amount of time that this condition (drain pipe flowing "mud") had existed was not established during deposition. It may have been a few hours or perhaps several days to a week or more. The Maintenance Person went to the site and observed about one inch of water flowing from this pipe and described it as "muddy water." He then notified the Owner who, in turn, notified the Engineer of the problem at about 3:30 pm. The Maintenance Person left the site for the evening at about 5:00 pm. Depositions indicate that neither the Owner nor the Engineer visited the site prior to the Maintenance Person's departure.

The Engineer confirmed that he had received a phone call from the Owner and was informed of the observations of the Maintenance Person about the drain pipe discharge with a "slightly muddy tint." The Owner was informed by the Engineer that it would not be unusual for some of the drains to have increased discharge due to the heavy and extended rainfall ending just a week or two prior to the incident. It was further reported that the Maintenance Person did not feel any soil or fines particles in the pipe discharge. The Engineer indicated he would visit the site the following morning.

At about 8:30 am on Friday, March 12, the Engineer was on the way to the site when he received a call from the Owner, who told him that the Maintenance Person reported that the drain discharge appeared to have a little soil material in it and more of a muddy tint. Upon arriving at the site sometime between 9:00 and 9:30 am, the Engineer noted that the reservoir pool was about 6 to 8 inches above normal, the stilling basin had some muddy discoloration, and the discharge from the drain pipe had increased. Upon further inspection, the Engineer noted that there was a single point of seepage exiting the foundation at the ground surface immediately downstream of the dam toe, west of the wing wall, above the level of the stilling basin, and away from the location of the 6-inch drain pipe discharge. The discharge exiting the ground surface was described as about a 1/2-inch diameter flow bubbling about 1/2 inch above the ground

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surface. The Engineer estimated the rate of flow to be 1/2 to 1 gallon per minute. There was minor evidence of soil particles (10 grains in one minute flowing over a fine screen) being transported in the discharge but there was no accumulation of sand material around the discharge area. The Engineer postulated that the flow from this discharge was traveling along the ground surface to the stilling basin and that some of the water was infiltrating down through the relief drain materials and into the discharge pipe and causing the flow from the pipe.

The Engineer then proceeded to complete an inspection of the outlet discharge conduit that was flowing, the toe of the dam both east and west of the location of the outlet discharge structure, the dam crest, and the reservoir pool along the upstream slope of the dam, looking for any seepage, signs of distress, or whirlpools. None were noted. He went back to the seep and, noting no change, left the site at 11:00 am to call a contractor.

At about 11:30 to 11:45 am, the Maintenance Person called the Engineer and noted that the flow from the 6-inch discharge pipe had increased. He then left the site for lunch. Upon his return, he noted a significant change in the seepage area. Although the timeline could not be precisely established, at about 12:00 to 12:15 pm, the Maintenance Person described seepage from an area about 20 to 30 feet southwest of the drain pipe discharge location, muddy in color and spraying 30 to 40 feet into the air. He immediately contacted the Engineer, who was just minutes from the site.

Upon arriving back at the site, the Engineer described the seep as spouting approximately 2 to 3 feet high, with a diameter of about 18 inches. He further noted, "Quite suddenly, the area around the boil appeared to liquefy and/or settle downward, and rapid erosion set in to the north [downstream slope of the dam] and to the south [downstream direction]" [authors' notes]. The erosion into the downstream slope of the dam progressed quickly. During deposition, the Engineer noted that the location of this seepage was 10 to 15 feet off the toe of the dam, and about 60 to 70 feet off the stilling basin and west side of the box structure. However, the location of the toe drains and the 1999 remedial construction in the area around the outlet works discharge structure and box culvert, along with the potential for clogging of these drain systems, could have substantially altered seepage patterns. The Engineer noted that the crest of the dam had breached and uncontrolled release of the lake pool began at approximately 12:25 pm. Figures 5 – 9 show a time series of the failure.

A photo taken after the reservoir drained showed a large sinkhole east of the breach in the upstream face of the dam (Figure 10), below what had been the normal pool elevation.

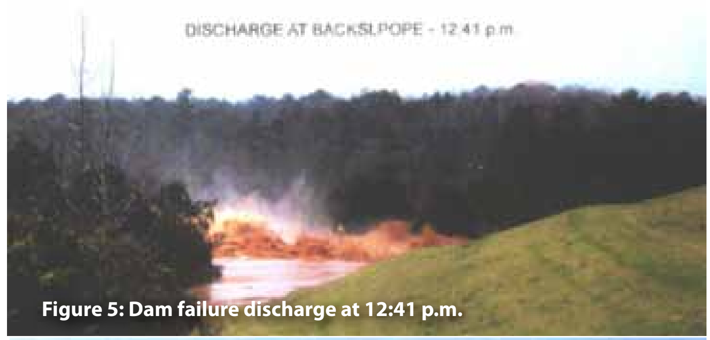

Figure 5: Dam failure discharge at 12:41 p.m.

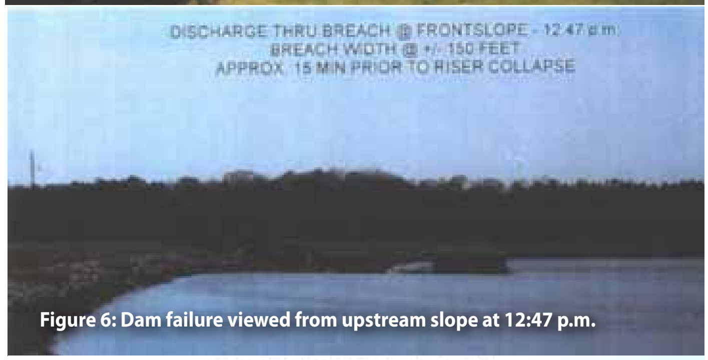

Figure 6: Dam failure viewed from upstream slope at 12:47 p.m.

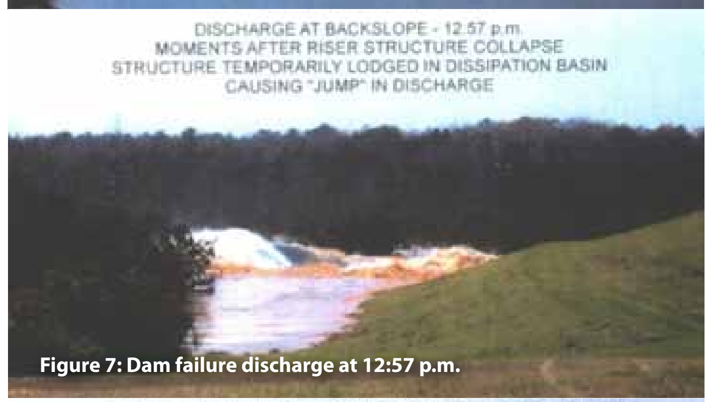

Figure 7: Dam failure discharge at 12:57 p.m.

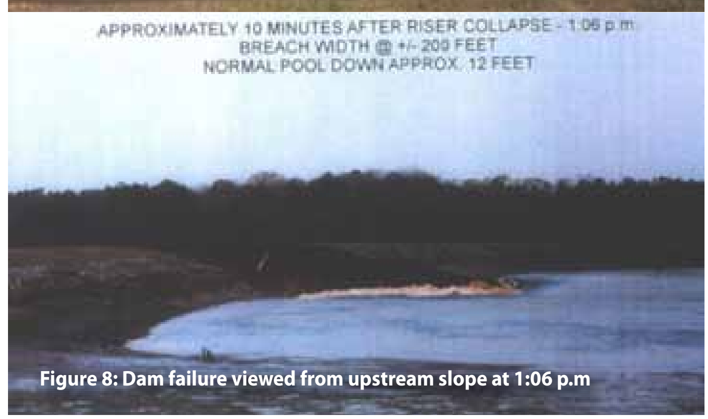

Figure 8: Dam failure viewed from upstream slope at 1:06 p.m

Figure 9: Dam failure discharge at 1:12 p.m

The breach that formed in the dam was in the general vicinity of the outlet conduit and resulted in total failure of the riser, the conduit through the embankment at the foundation contact, and the outlet discharge structure (Figure 12). The distress indicators discussed above are located as shown below on Figure 11.

The physical mechanism of the failure was never conclusively established during the subsequent investigation and litigation phases of the project. While several hypotheses were postulated by different parties, the authors' examination of the information from the investigations and trial activities, along with their general experience with seepage failure modes, suggests that the failure mode development process was complex. As discussed further below, contributing factors may have included use of highly erodible soils for the embankment, the defects in the outlet conduit, lack of effective seepage control in the central core of the dam, and inadequately designed and constructed seepage filter and collection systems in the downstream portion of the


Figure 10: Sinkhole on the upstream face after failure


Figure 12: Dam breach

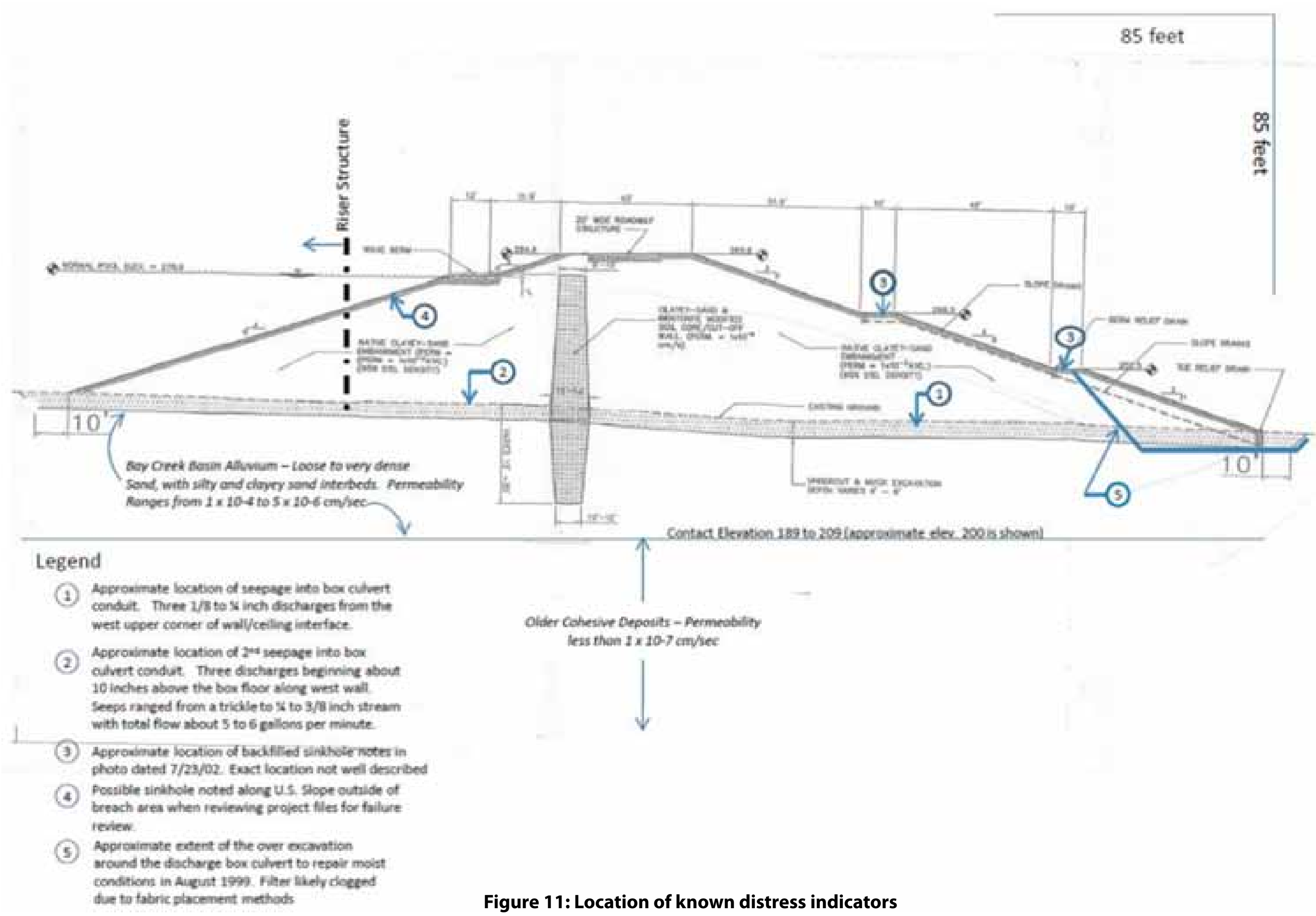

Figure 11: Location of known distress indicators

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dam and foundation. The lack of adequately designed, installed, and monitored instrumentation in response to the observed seepage distress indicators at the dam likely contributed to the lack of early detection and further corrective actions that may have prevented failure of the dam.

PHYSICAL FACTORS IN THE DAM FAILURE

Ferguson et al (2014) provided a thorough technical analysis of the failure focusing on physical factors and processes, and noted the following:

- In general, piping may have begun during first filling of the reservoir, and continued to develop until the failure 13 years later, with the piping process accelerating during the last 24 to 48 hours before failure, and especially during the last 2 to 4 hours.
- The piping process likely involved a complex sequence of cycles, with a combination of the following pathways: along the backfill/culvert interface, along the backfill/native soil interface, into unfiltered defects in the culvert, and through the embankment and foundation materials.
- Contributing physical factors to the piping likely included the following:
  - Highly erodible soils (primarily silty sands) used for the dam embankment and in the upper foundation in the general vicinity of the outlet conduit
  - Ineffective and heterogeneous core wall in the dam, with permeabilities generally too high for a core wall and varying by up to three orders of magnitude
  - Ineffective cutoff wall in the dam foundation, in terms of both (a) having too high a permeability and (b) not being deep enough, resulting in a 6' to 10' vertical "window" of relatively permeable material between the bottom of the cutoff and the underlying older low-permeability cohesive materials, with this window causing "mounding" of the phreatic surface downstream of the core/cutoff wall
  - Numerous defects in the conduit
  - Lack of a filter diaphragm or other effective seepage filter around the conduit
  - Lack of an effective toe drain system, with the remedial backfill and toe drain being susceptible to clogging, which could then redirect seepage elsewhere, including downstream of the toe

The paper by Ferguson et al (2014) provides much more detail, and the authors conclude that their technical analysis strongly suggests that "construction of a full and effective cutoff, a conduit without defects, and/or an effective internal embankment and foundation drainage system under the downstream shell of the dam would have significantly improved the safety of the dam and prevented its failure."

HUMAN FACTORS CONTRIBUTING TO THE FAILURE

The intention of this article is not to find fault or assign blame by judging in hindsight, and, indeed, it appears that the parties involved with Big Bay Dam did often make good faith efforts. For example, the Owner demonstrated the willingness to spend money to properly inspect, maintain, and remediate the dam as necessary, and the Engineer recognized in the 2002 inspection report that "… early detection of potential deficiencies are the best way to control, mitigate, and correct problems that could magnify and lead to disastrous results."

However, to understand the human factors that contributed to the failure, and thereby discern potential lessons learned, an assessment was made of the specific attitudes, actions, and inactions of the various parties throughout the history of the dam prior to failure. In this regard, it appears that the parties were not sufficiently vigilant with regard to preventing failure, and as a result there were numerous shortcomings relative to following the set of best practices which have generally proven effective in preventing the failure of dams. Based on our review of the available information, the following are key examples of this:

- The Engineer who designed the dam appeared to have had limited experience in the design and construction of dams, particularly dams of a size and type similar to Big Bay Dam. This could have led to design and construction practices that were not state-of-practice at that time.
- The original design plans were inadequate, with several inconsistencies within the plans, as well as between the plans and the as-built dam. In addition, the plans had no Professional Engineer's seal, thus not meeting basic expectations of professional practice. All of this suggests a general lack of attention to the design process and associated quality control.
- Highly erodible materials existed in the upper foundation of the dam and were used for construction of the dam. Adequate provisions were not included in the design and construction to provide a typical margin of safety associated with the presence of these materials.
- The design and construction of the cutoff wall were inadequate. Effective cutoff of foundation seepage pathways could have been achieved by extending the cutoff trench about 10 feet deeper, to the top of an underlying impervious clay stratum. Failure to achieve an effective cutoff substantially increased foundation seepage pressures, flows, and the potential for piping while providing relatively little cost savings.
- Need for effective seepage filters and drains in the dam, foundation, and around the outlet conduit, especially for a dam of this size and hazard level, was well known in the dam engineering community at the time of the original dam design, yet no such provisions were included for Big Bay Dam. The dam generally lacked sufficient, diverse, and redundant measures to control seepage and piping, instead proving highly vulnerable to formation of sequentially linked piping pathways. The use of filter fabric, combined with the unsuitable installation procedures for the fabric, resulted in a very high potential for filter defects and clogging. Instead of providing for safety, the very limited filter/drainage provisions that were included in the original design, as well as subsequent efforts to address seepage distress around the conduit, likely increased the risk of failure of the dam.
- The Owner relied on the Engineer by apparently entrusting him with the original design, all of the remedial designs, the primary engineering inspections of the dam, and the investigation of the dam failure. By contrast, a best practice would be to draw on diverse perspectives and conduct a peer review.
- It appears that construction of Big Bay Dam was the first major project of the contractor, which raises questions about the contractor's qualifications.
- The construction inspections performed were apparently insufficient to prevent or correct problems with construction quality, such as defects in the conduit, deficient quality of the toe drain construction, and ineffectiveness of the core/cutoff wall (no core wall is visually apparent in photos of the dam section taken after the breach, e.g. Figure 12).
- Prior to 2002, it is not clear that the dam was inspected with sufficient frequency or competency by the Owner or Engineer. The State Dam Safety Program did perform some inspections during this period, but the agency was understaffed and did not have the resources to spend substantial time inspecting and evaluating the 250+ high-hazard dams under its jurisdiction. And while the Owner's Maintenance Person also performed inspections, apparently diligently and frequently during the few years prior to the failure, he had no engineering background or formal training in dam inspections, and thus may have provided a false sense of security to the Owner.
- Despite its relatively large size and high hazard, the dam lacked adequate instrumentation and provisions for monitoring of embankment and foundation water pressures and the changing seepage conditions that developed in the vicinity of the outlet works conduit.
- Overall, numerous distress indicators and other warning signs of a developing piping/internal erosion failure mode were apparent over a period of more than a decade. These included: substantial leakage into the conduit in multiple and changing locations, wetness of the downstream face, need for remediation of the downstream face in the vicinity of the conduit, sediment accumulation in the stilling basin, and sinkhole formation. Yet, none of these warning signs were addressed in a manner demonstrating adequate appreciation of the developing piping failure mode. The Engineer instead dismissed the warning signs as insignificant on several occasions. Moreover, some of the remedial actions taken may have actually contributed to the piping failure due to inadequate design and/or construction.

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In summary, it appears that the Engineer and contractor may have lacked sufficient qualifications and diligence for the design and construction of the dam (and lacked sufficient awareness of their limitations); the qualifications of the Engineer were also apparently insufficient for subsequent dam inspections and remedial work; and the Owner excessively and overconfidently relied solely on the Engineer for many years, rather than soliciting second opinions and peer review from other qualified engineers. As a result, the dam design, construction, and remedial work were inadequate in many aspects, and numerous warning signs of developing piping over a period of more than a decade were not adequately addressed. If these combined deficiencies in human factors – which interacted with physical factors in complex ways, as described above – had not been present, it is very unlikely that the dam would have failed.

CONCLUSIONS

These physical and human factors involved in the failure of Big Bay Dam were discussed in detail during a Soapbox Session at the 2014 ASDSO national conference. Below, we summarize a list of best practices developed by the Soapbox attendees, along with comments about each practice as it relates to Big Bay.

- Have adequate state staffing.
  - *Prior to the failure of Big Bay Dam, the state of Mississippi only had one engineer in the Dam Safety Program. The inspections that were conducted by the State were done by technicians. In addition to adequate staffing, staff also needs to be adequately trained. Perhaps there should be standards that define what constitutes adequate training for dam safety regulators.*
- Conduct adequate dam owner training.
  - *The Dam Owner did not have an adequate understanding of the state permitting requirements for the repair work that was done at the dam. As such, most of the work done at the dam in the 90s was unpermitted, and many of the distress indicators were unknown by the State prior to the failure.*
- Have a qualified contractor.
  - *The construction of Big Bay was the first major project for the contractor. Contractors for the construction of dams such as Big Bay should have prior dam construction experience.*
- Have an operation and maintenance (O&M) manual with distress indicators described.
  - *In the case of Big Bay, the dam was frequently inspected by the Maintenance Person. Perhaps if he had an O&M Manual with distress indicators he might have been able to detect and interpret the warning signs observable at the dam.*
- Require dam owners to notify the State Dam Safety Program if distress indicators occur.
  - *There were major repairs done at Big Bay without even notifying the State. Dam Safety Program s should be made aware of even minor seepage prior to any type of drainage system being installed.*
- As an industry, determine qualification standards or recommendations for engineers who work on dams and have State Dam Safety Programs maintain lists of qualified engineers for dam owners. Have requirements in place to ensure that dam owners hire qualified engineers.
  - *The qualifications of the consultant that designed Big Bay Dam were questionable; however there were no requirements or standards in place that prevented this engineer from designing the dam.*

A key lesson learned from the Big Bay Dam failure is that having a thorough knowledge and documentation of the design, construction, and performance history of a dam is vital for inspections, detection of problems, and implementation of effective repairs. Proper documentation also can help if a dam fails so state dam safety programs can conduct successful investigations and determine the causes of the dam failure

Often with seepage and piping, when there are significant changes in the location or volume of seepage, these changes can be linked back to changes in operation or repairs made to the dam. Having knowledge of this "cause and effect" will give dam owners and their engineers a much better understanding of what is occurring within the dam. Perhaps if a trained individual had known the entire history of Big Bay Dam before it failed he or she could have prevented the failure.

Below are some tips for being prepared to conduct successful dam failure investigations, which are contained in the ASDSO 2011 Dam Failure Investigation Guidelines. Utilizing these tips and other information from this guideline can help State Dam Safety Programs be prepared for dam failures:

- Review relevant case studies of past failures and the response to such failures to extract applicable lessons learned.
- Review the State's Dam Safety Laws and Regulations to determine whether the State has the authority to investigate dam failures and incidents and if that authority could be extended to an external investigation team.
- Train/communicate with field staff about dam safety incident response and failure investigation procedures (such as video, safety, documentation, timeline, etc.).
- Thoroughly document any known problems with the dam and keep good records.
- Incorporate this guidance into State program emergency action plans/policies/procedures.
- Explore ways of funding and rapidly mobilizing resources (e.g. equipment and materials) for responding to a dam incident.

DISCLAIMER

The assessment of the failure of Big Bay Dam by the authors was conducted solely for the purpose of advancing the state of practice of dam safety engineering in the State of Mississippi and nationally. No other purpose is intended or implied and the authors assume no other responsibility for the findings and conclusions summarized here or in related technical publications.

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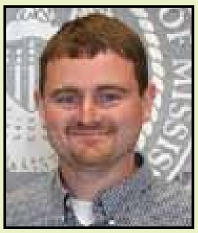

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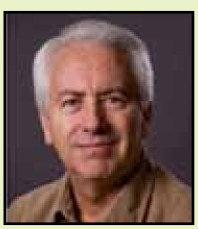

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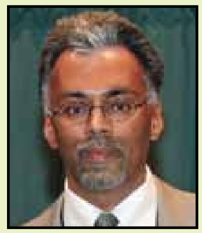

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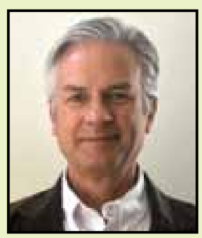

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