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Overtopping Performance of Earthen Dams during Record Flooding in Columbia, South Carolina

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ABSTRACT

South Carolina experienced what has been described as a 1,000-year flood on October 4 and 5, 2015. Widespread rainfall from Hurricane Joaquin pounded the state's capital city, Columbia, with over 20 inches of rain recorded in many locations. As a result, over 70 miles of Interstate 95 had to be closed, in addition to local roads and bridges, and thousands of residents had to flee their homes. State-wide, 36 dams failed – 31 state-regulated, 1 federally-regulated (on Fort Jackson), and 4 unregulated. The South Carolina Department of Health and Environmental Control (DHEC) issued emergency orders on 75 additional dams in the state, with the vast majority of them privately-owned earthen dams. Sadly, there were 19 flood-related deaths, including a first responder whose work truck was swept away by the flood. Millions of dollars in property damages were incurred.

This paper summarizes the historic storm and associated flooding of October 2015 in South Carolina, including the 74.5 mi^2 Gills Creek Watershed in Richland County where 16 inches of rain was recorded in just 6 hours. It documents the overtopping performance of a number of earthen dams, including the overtopping failure and planned restoration of Gibson Pond Dam, as well as the satisfactory performance of Forest Lake Dam that had fabric-formed concrete overtopping protection on its crest and downstream slope. It is anticipated that the information presented in this paper would be of benefit and interest to those involved in dam safety.

Keywords: *dams, overtopping, embankments, flooding, failure, protection.*

1. FLOODING PRODUCED BY RECORD RAINFALL EVENT

The National Oceanic and Atmospheric Administration (NOAA) had predicted a below-normal 2015 Atlantic hurricane season of June 1 through November 30 due to a suppression of activity primarily attributed to El Niño. NOAA predicted a 70% chance of 6 to 11 named storms, with no more than two major (Category 3 or greater) hurricanes (www.noaanews.noaa.gov). However, historic records included instances where, during a below-normal season, a hurricane has had devastating impacts on communities. For 2015, NOAA increased the resolution of their Hurricane Weather Research and Forecasting model and introduced a new means to communicate storm surge warnings to communities via a map that would highlight areas at risk for flooding. Their predictions were reasonably accurate, with 11 total storms, 4 hurricanes, and 2 major hurricanes (Hurricanes Danny and Joaquin) occurring in 2015.

Hurricane Joaquin became a tropical storm on September 29 and rapidly intensified into a Category 3 hurricane. After moving southwest and passing over the southern Bahamas, it intensified further to nearly a Category 5 with sustained 155 mph winds and overwhelming impacts to numerous islands from severe and sustained storm surges of 5 to 8 feet. Eighty-nine deaths and about $650 million in economic damages were reported and it is viewed as the worst storm to batter the Bahamas and adjacent islands since 1866. As the storm began moving north, considerable uncertainty existed in path projections from numerical models (see Figure 1). The National Weather Service was forecasting more than 10 inches of rain that could possibly cause widespread flooding in southeast South Carolina.

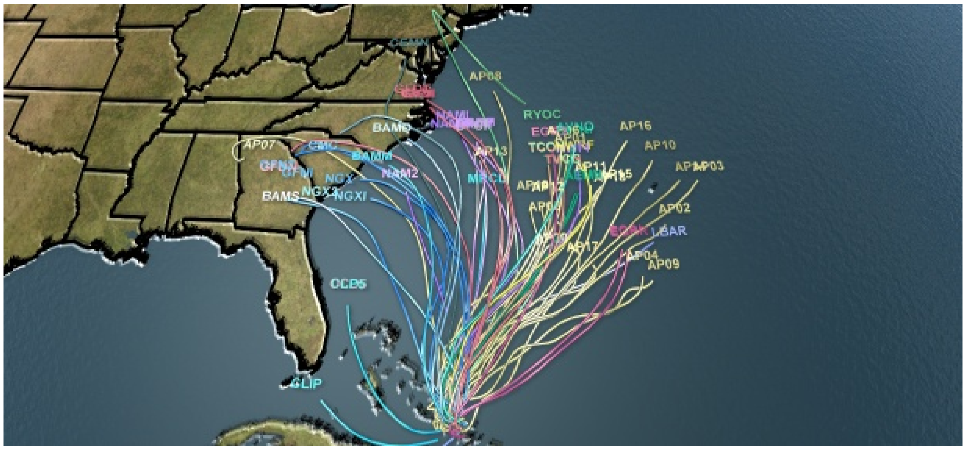

Figure 1. Numerical model path projections for Hurricane Joaquin
on October 1, 2015 (www.wordpress.com)

However, by 2:00 a.m. EST on October 1, the National Hurricane Center had issued no hurricane warnings or watches for South Carolina (www.nhc.noaa.gov). Rain began that afternoon, but Hurricane Joaquin remained several hundred miles southeast and never directly impacted the United States. Nevertheless, the rain intensified on October 2 and new precipitation records were set during the next 5 days [see Figure 2, (Dolce 2015)].

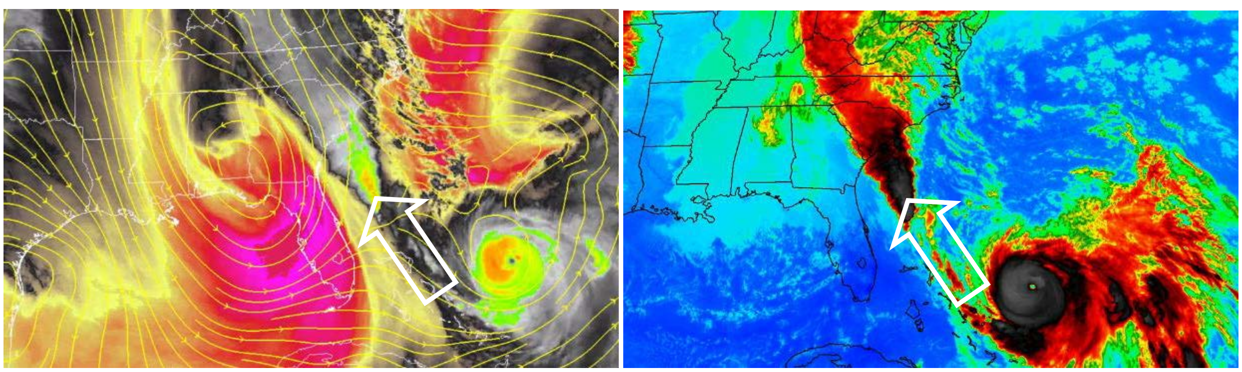

Figure 2. Satellite imagery of climatic circumstances contributing to record-setting heavy rains in South Carolina October 1-5, 2015: water vapor and winds Oct. 3 (A) (National Weather Service, Columbia, South Carolina) and infrared rainfall imagery (B) (NASA)

According to the Chief Meteorologist of Accuweather, a unique and highly unusual combination of events took place that produced record rains in South Carolina. Specifically, a storm front reversed direction along the Atlantic seaboard, a low pressure region existed over portions of Alabama and Florida, and two storms stalled – a non-tropical storm south of Florida and Hurricane Joaquin. The result was a devastating amount of moisture siphoned from these two storms (primarily Joaquin) and directed towards South Carolina. Truly a historic, long-duration storm occurred. Local total rainfall amounts exceeding 25 inches (see Figure 3) were recorded in Charleston and Berkeley Counties, with total rainfall amounts greater than 12 inches across most of the state (www.weather.gov, accessed April 2, 2016). In Richland County, the Gills Creek Watershed (74.5 mi^2) experienced over 16 inches of rain in only 6 hours. The City of Columbia reported a new 24-hour record rainfall of 7.7 inches. Charleston Airport rainfall amounts set new records for greatest 1, 2, 3, and 4 day totals of 11.5, 14.31, 15.92, and 17.29 inches, respectively. From October 1-6, Charleston received 16.43 inches, the Charleston Airport received 17.32 inches, Mount Pleasant received 27.1 inches, Georgetown received 23.8 inches, and Kingstree received 24.75 inches. Even after October 6, periodic rainfall events continued for the next 5 days, preventing the flood waters from receding.

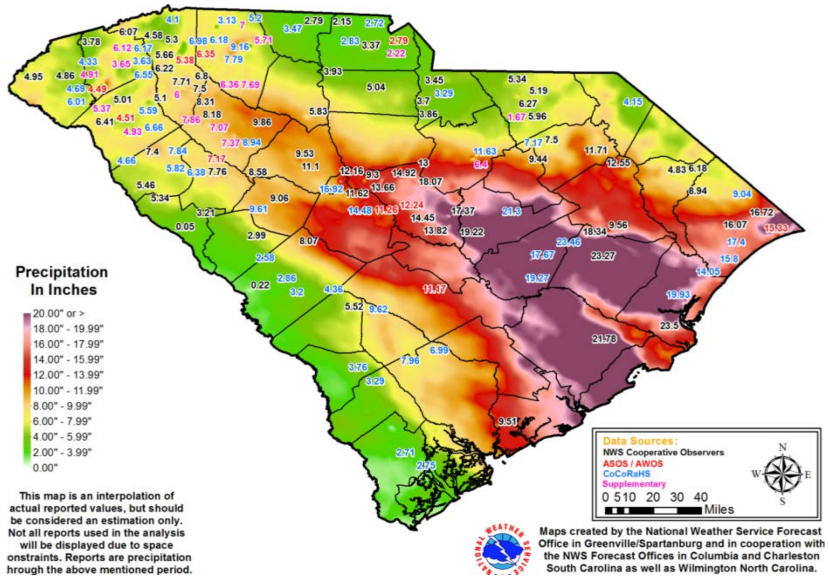

Figure 3. Rainfall estimates for South Carolina through Oct. 5, 2015 (www.weatherflow.com)

2. EMERGENCY RESPONSE

The U.S. Geological Survey (USGS) operates approximately 170 stream gage stations in South Carolina that can provide data to assist with preparing flood forecasts and documenting inundation levels. According to a USGS Preliminary Report (Feaster 2015) issued on December 1, 2015, record peak stages were recorded at 17 stream gages in South Carolina between October 1 and 11, with an additional 15 streamgage readings ranked within the five highest historic stage measurements of each station's data series.

An estimated 4.4 trillion gallons of water fell on South Carolina. As a result, thousands of residents left their homes to escape life-threatening floods. Over 410 local roads and bridges were closed, including over 70 miles of Interstate 95. About 2,000 auto collisions occurred across the state because of the storm. More than 200 water rescues were performed and over 1,100 South Carolina National Guard members were activated. Drinking and wastewater systems were badly damaged and more than 50,000 residents were without power (see Figure 4a). The South Carolina Department of Health and Environmental Control (DHEC) issued emergency orders on 75 dams in the state, with the vast majority of them privately-owned earthen dams (www.scdhec.gov). State-wide, 36 dams failed – 31 state-regulated, 1 federally-regulated (on Fort Jackson), and 4 unregulated (see Figure 4b). Sixteen dams failed in Richland County alone and several more were in danger of failing. Eleven of these dams showed repeated deficiencies in previous dam safety inspections (including inadequate spillway capacity and heavy vegetation on the embankment), which had not yet been addressed. Most tragic of all were the 19 flood-related deaths (11 due to drowning), including a first responder whose work truck was swept away by the flood, and a report of several motorists trapped below failing dams that were also eventually swept away. Agricultural loses of $376 million were estimated by the South Carolina Department of Agriculture. Total economic losses were estimated by insurance broker Aon plc to be about $2 billion.

Figure 4. Flooding in the City of Columbia (A) (photo by Sean Rayford) and
at the Columbia Riverfront Canal (B) (photo by South Carolina National Guard)

3. OVERTOPPING PERFORMANCE OF DAMS

3.1. Gills Creek Watershed

The Gills Creek Watershed is located in Richland County and includes the northeastern portion of Columbia, and portions of Forest Acres, Arcadia Lakes, and Fort Jackson. The watershed covers 74.5 square miles and contains Gills Creek and five tributaries, with 23 state-regulated dams and an unknown number of smaller, unregulated dams, impoundments, and ponds. The majority of the large impoundments are managed by home and lake owner associations, and each includes an earthen dam ranging between 13 and 30 feet in height. Of the 23 dams regulated by DHEC, 17 are classified as High Hazard, 4 as Significant Hazard, and 2 as Low Hazard. Eleven of the high hazard dams were overtopped during the October 2015 flood, and three of them breached. Five others were damaged sufficiently to represent a high concern for potential failure during a future significant rainfall event due to an increased susceptibility to overtopping or internal erosion. Current state dam safety standards (in accordance with the Dams and Reservoirs Safety Act of 2008, and associated Regulations) require high hazard dams to safely pass a design flood between the ½ PMF and full PMF, significantly greater than that produced by the October 2015 flood.

HDR Engineering was contracted by DHEC following the flood to prepare an assessment of the regulated dams within the watershed and to develop a modeling tool "to evaluate future flooding potential and dependency between impoundments for regulating runoff in the basin." HDR found significant variation with the capability of the dams to safely pass flood events, including many with inadequate spillway capacity or some degree of spillway impairment. HDR also observed poor maintenance practices (including the presence of trees and woody brush on embankments), steep embankment slopes, low areas of embankment crests, waterlines and conduits within embankments not associated with operation of the dam, and inadequate construction materials susceptible to corrosion (including corrugated metal pipes). A HEC-HMS model of the Gills Creek Watershed was developed to simulate runoff from future flood events and assess the performance of the damaged regulated dams for floods up to the 100-year storm for the identification of structures of high concern. Their final report recommended a watershed-wide evaluation of hazard classification, spillway adequacy, condition and design assessment, maintenance practices, and emergency action plans (HDR, 2016). Four embankment dams within the watershed are shown and described below.

3.1.1. Cary's Lake Dam

Cary's Lake Dam was located on Jackson Creek, with a maximum height of 20 feet and active storage capacity of 400 acre-feet. The dam consisted of a 350-foot-long earthen embankment with paved crest roadway, a drop inlet concrete service spillway with 6.5-foot-square outlet conduit, and concrete auxiliary overflow spillways on both abutments.

The upper northern portion of the Gills Creek Watershed above Cary's Lake Dam has a drainage area of 19.8 square miles and includes 15 state-regulated dams.

This high-hazard dam was completely breached to streambed on Sunday morning, October 4, during an estimated 4 feet of overtopping (see Figure 5). Only one upstream, unregulated dam (Pine Tree Lake Dam) failed during the flood, but it is estimated that this failure occurred several hours after the overtopping and breach of Cary's Lake Dam (unconfirmed). The breach of Cary's Lake Dam nearly extended to the concrete spillways on both abutments, and measured 137 feet at the dam crest and 70 feet at the dam foundation for the 20-foot depth. Representative samples of the failed embankment soils were classified as a poorly-graded sand with silt (SP-SM) (Tabrizi, 2016). Under the current breached conditions, the overall concern for this site for future flood events is considered to be low (HDR, 2016). Privately-owned by an association of 46 homeowners, this dam was among those regulated by DHEC, and the public roadway on the crest was state-maintained. Preliminary repair estimates approach $1.5 million, with as yet undetermined potential funding sources.

Figure 5. Full breach of Cary's Lake Dam embankment at maximum section and low-level outlet (photo courtesy Schnabel Engineering).

3.1.2. Spring Lake Dam

Spring Lake Dam is located downstream of Cary's Lake Dam on Jackson Creek, with a maximum height of 17 feet and active storage capacity of 290 acre-feet. The approximately 400-foot-long earthen embankment dam has a paved crest roadway, an 84-foot-wide concrete overflow auxiliary spillway on the left abutment, and a drop inlet concrete service spillway with 3-foot-diameter outlet pipe on the right abutment.

This high-hazard dam sustained significant damage to the embankment and concrete auxiliary spillway due to overtopping by an estimated 4 feet (see Figure 6). The overtopping failure of Cary's Lake Dam may have increased the peak flood levels downstream due to the breach of the upstream impoundment. The right sidewall of the auxiliary spillway washed out, allowing significant erosion of the adjoining embankment. Several concrete chute floor slabs were also washed away, exposing the structure foundation. Overtopping flows resulted in significant headcutting erosion and scour of an approximately 100-foot-long section of the downstream embankment slope, extending to the dam crest in several locations. Representative samples of the embankment soils were classified as a clayey sand with silt (SC-SM), which may have provided some erosion resistance (Tabrizi, 2016). Although undesirable from a dam safety perspective, several large trees growing on the downstream slope may have influenced flow velocities somewhat and the tree roots may have resisted embankment erosion. High tailwater from Forest Lake immediately downstream could have also reduced the overtopping damage to the embankment. The HEC-HMS model developed by HDR indicates the 10-year/24-hour storm could result in a peak reservoir water level within one foot of the Spring

Lake Dam crest, suggesting a potential for the embankment to again overtop for relatively frequent flood events. Under the current damaged conditions, the overall concern for this site for future flood events is considered to be high due to the potential for further erosion and failure of the embankment at the auxiliary spillway (HDR, 2016). Preliminary repair estimates approach $0.5 million.

Figure 6. Extensive headcutting erosion and scour damage at the downstream slope of Spring Lake Dam (A) and at the right sidewall of the auxiliary spillway (B). Photos courtesy Schnabel Engineering.

3.1.3. Forest Lake Dam

Forest Lake Dam is located downstream of Spring Lake Dam on Gills Creek, with a maximum height of 23 feet and active storage capacity of 730 acre-feet. The purposes of the dam were first to impound water for recreation and later, to provide a water supply for Fort Jackson. The 600-foot-long dam consists of left and right earthen embankments on either side of a 77-foot-wide concrete slab-and-buttress spillway structure with low-level outlet. The gated spillway features four 2-foot-high by 17.75-foot-long crest gates (added in 1942), each operated by a hand winch located on a concrete bridge deck at the dam crest. The low-level outlet includes a 48-inch-diameter sluice gate and 4- by 4-foot concrete culvert to the right of the crest gates. A similar culvert to the left of the crest gates was modified for a 24-inch-diameter cast iron water supply pipe to Fort Jackson, which was later abandoned and plugged when the lease held by the U.S. Army Corps of Engineers (USACE) expired in 1991. An 11-foot-wide uncontrolled concrete auxiliary spillway is located on the left abutment. Channel erosion protection below the spillway was provided by concrete-filled bags. The earthen embankments have a crest width of 14 feet (left) and 10 feet (right), with an upstream slope of 3H:1V and a downstream slope of 2H:1V. The embankments were modified by the USACE in 1988 to accommodate the full PMF by the installation of fabric-formed concrete articulating mat overtopping protection on the dam crest and embankment slopes. Total discharge capacity at this location is an estimated 10,000 cfs.

This high-hazard dam performed very well during an estimated 3 feet of overtopping (see Figure 7), and is considered to be of low concern for future flood events (HDR, 2016). Large riprap was placed in scoured portions of the approach and outlet channels for the concrete auxiliary spillway following the flood to provide additional erosion protection. The dam overtopping breach flow from Cary's Lake Dam was safely passed over Forest Lake Dam, which is located below the confluence of Jackson and Gills Creeks. The upstream failures of Upper (North) Rocky Ford Lake (or Overcreek Road) Dam and Lower Rocky Ford Lake Dam on Gills Creek, with maximum heights of 11 and 20 feet respectively, occurred the day after the failure of Cary's Lake Dam, and did not contribute to the maximum flood levels recorded at Forest Lake Dam due to their relatively small storage volumes. The earth-lined auxiliary spillways at these two upstream dams were breached during flood releases, without dam overtopping.

Figure 7. Fabric-formed concrete overtopping protection (A) and gated spillway structure (B) for Forest Lake Dam (photos courtesy Schnabel Engineering)

3.1.4. Lake Katherine Dam

Lake Katherine Dam is located downstream of Forest Lake Dam on Gills Creek, with a maximum height of 14 feet. It was originally constructed in 1940 and modified by the USACE in the 1990s. The 900-foot-long dam features a 100-foot-wide grouted riprap overflow crest spillway with wooden flashboards between left and right earthen embankment sections, and a 100-foot-wide auxiliary earthen overflow spillway on the left abutment. Two concrete drop inlet spillway structures are located on the right abutment with a 2-foot-diameter reinforced concrete outlet pipe and a 6-foot-diameter corrugated metal outlet pipe. The embankment sections have a crest width of approximately 20 feet with generally 2H:1V slopes. The dam crest is grass-covered, while the left embankment slopes contain heavy underbrush with some mature trees along the downstream toe, and the right embankment is covered with trees and brush. The state-regulated dams within the Gills Creek Watershed are all located above Lake Katherine Dam, within a 53.8 square mile drainage area. Lake Katherine is the largest reservoir in the watershed, with a surface area of 142 acres and 1,000 acre-feet of active storage.

This high-hazard dam performed satisfactorily during an estimated 4 feet of overtopping, with only minor erosion (see Figure 8), and is considered to be of low concern for future flood events (HDR, 2016). Overtopping performance of the earthen dam was apparently greatly improved by very high tailwater (approaching the level of the dam crest) from Wildcat Creek, which extends near the downstream toe along much of the left embankment section and enters Gills Creek below the grouted riprap overflow crest spillway. The 22-foot-high Semmes Lake Dam on Wildcat Creek (within Fort Jackson) failed early Sunday morning, sending breach flows downstream at about the same time that Lake Katherine Dam was overtopping. Overtopping performance of the right embankment section may have been improved by the presence of several large trees on the crest and slopes (although generally undesirable), which could have reduced flow velocities and provided some degree of erosion protection. The left abutment auxiliary spillway is grass-lined with a jute mat and experienced minor to moderate erosion (up to a reported 2 feet), probably also benefitting from the high tailwater from Wildcat Creek. Representative samples of the embankment soils were classified as a poorly graded sand (SP), which would not have provided much erosion resistance (Tabrizi, 2016).

Figure 8. Debris deposited on crest of left embankment during overtopping (A) and heavily wooded right embankment beyond overflow spillway crest (B) at Lake Katherine Dam (photos courtesy Schnabel Engineering).

3.2. Twelvemile Creek Watershed

Twelvemile Creek is located in Lexington County and runs from the Town of Gilbert, through the Town of Lexington and ends at the Lower Saluda River. It includes a string of impoundments, including the Barr Lake, Gibson Pond, and Old Mill Dams located in series near the lower end of the watershed. These three DHEC-regulated dams were the subject of numerical dam breach analyses performed in 2000, based on the assumed failure of Barr Lake Dam under both sunny day and flood conditions, and subsequent overtopping, in succession, of Gibson Pond and Old Mill Dams. Flood conditions analyzed by DHEC included the 100-year flood and the ½ PMF.

3.2.1. Barr Lake Dam

Barr Lake Dam is a 14-foot-high embankment dam located west of Lexington on Twelvemile Creek, with a drainage area of 27.1 square miles and active storage capacity of 243 acre-feet. The 625-foot-long dam is believed to be a homogeneous earthen embankment founded on soil, and contains two concrete service spillways located near the center and right portions of the embankment, and a grass-lined auxiliary spillway on each abutment. The left bay of the center spillway contains a 6-foot-wide overflow crest, while the right bay formerly housed a turbine that has since been abandoned. The right spillway consists of a channel created by two concrete walls, with a 25-foot-wide metal control weir supported on timber piles. Both concrete spillways include bridges at the dam crest. The left auxiliary spillway is 65-feet-wide and well maintained, while the right auxiliary spillway is only 30-feet-wide and heavily vegetated.

Barr Lake Dam was privately-owned and the centerpiece of a new housing development with more than 300 proposed home sites. It was classified by DHEC as a significant hazard dam and was breached by the October flood (see Figure 9). The breach width was approximately 60 feet at the dam crest and 30 feet at the foundation, based on a topographic survey of the site following dam failure. Failure appears to have occurred due to piping at the location of an abandoned concrete conduit to the left of the center-most concrete spillway. Although the auxiliary spillways both operated, the dam did not appear to have been overtopped. A numerical hydraulic model of the dam developed by Schnabel Engineering indicated dam overtopping of approximately 0.6 feet during a rainfall event of the magnitude experienced during the October flood. It is believed that the localized dam breach occurred prior to the peak inflow, thus preventing dam overtopping. Both auxiliary spillways were also noted in the model to operate for floods as small as the 2-year flood event. Representative samples of the embankment soils were classified as a clayey sand with silt (SC-SM), which may have provided some erosion resistance (Tabrizi, 2016).

Figure 9. Embankment breach at center of photo (at arrow), with two concrete spillways visible to right and approach channel to left abutment auxiliary spillway visible in the foreground, at Barr Lake Dam (photo courtesy Schnabel Engineering)

3.2.2. Gibson Pond Dam

Gibson Pond Dam was a 15-foot-high embankment dam owned by the Lexington Department of Public Works as a recreational feature located near the downtown area, offering picnic tables, a fishing dock, and walking trails. The impoundment had a normal surface area of 28 acres and active storage capacity of 128 acre-feet, with a total drainage area of 30.5 square miles. The 300-foot-long dam was completed in 1900, and was believed to be a homogeneous earthen embankment, with a concrete overflow spillway gravity section on the right abutment. It included a pedestrian bridge supported on piles, and four slide gates within the concrete gravity section for low-level releases. It was classified by DHEC as a significant hazard dam, and the earthen portion was washed away due to overtopping during the October flood (see Figure 10). The dam breach extended from the concrete gravity section to the left abutment, and measured 70 feet at the dam crest and 58 feet at the dam foundation. Representative samples of the embankment soils were classified as a well-graded sand (SW) (Tabrizi, 2016).

Figure 10. Breach of Gibson Pond Dam embankment (A) and remaining concrete gravity overflow section (B). Photos courtesy Schnabel Engineering.

3.2.3. Old Mill Dam

Old Mill Dam was a privately-owned earthen embankment located in Lexington on Twelvemile Creek, just upstream of the East Main Street Bridge. It was a 14-foot-high embankment dam with a concrete overflow spillway and low-level gated outlet structure on the right abutment. A 48-inch-diameter riveted steel penstock with gated intake structure was provided at the left abutment to supply water to a hydroelectric turbine. The 420-foot-long dam was classified by DHEC as high hazard due to the potential for loss of life in the event of failure. Prior to the October flood, the reservoir had been drained for planned repairs to the embankment following the development of a sinkhole at the crest immediately downstream of the left abutment intake structure and along the general alignment of the steel penstock, believed to be due to internal erosion. The repairs designed by Schnabel Engineering were to include concrete encasement of a portion of the penstock and the provision of a filtered diaphragm drain and 6-inch-diameter collector and outlet pipes.

Breach flows from Barr Lake and Gibson Pond Dams caused overtopping and failure of the dam embankment (see Figure 11). The breach extended from the left abutment structure, fully exposing the penstock, and measured 104 feet at the dam crest and 82 feet at the foundation. Representative samples of the embankment soils were classified as a clayey sand with silt (SC-SM) (Tabrizi, 2016). Repairs to restore the impoundment are estimated to cost up to $5 million.

Figure 11. Breach of Old Mill Dam embankment near left abutment (A) and exposed penstock (see arrow) (B). Photos courtesy Schnabel Engineering.

4. POTENTIAL REPAIRS TO SELECTED DAMS

4.1. Gibson Pond Dam

Schnabel Engineering recently completed hydrologic and hydraulic analyses of Gibson Pond Dam for the City of Lexington (Schnabel, 2015). This includes the analysis of the watershed and the spillway discharge capacity prior to failure of the dam, determination of precipitation amounts and areal distributions for the various storm events utilized in the analysis, and development of a HEC-HMS model to route storm runoff through the existing reservoir and dam. Based on these analyses, the dam in the configuration prior to failure was incapable of passing and/or storing runoff associated with the DHEC design storm, which for this site is the ½ PMF event. Based upon discussions with DHEC representatives, the dam will likely be re-classified as a Category I, or High Hazard, due to the potential failure of downstream structures, such as Old Mill Dam, should the subject dam fail. Evaluations of rehabilitation alternatives are currently underway, including overtopping protection, in order to increase the hydraulic capacity of Gibson Pond Dam to meet regulatory requirements.

4.2. Barr Lake Dam

Preliminary hydrologic and hydraulic analyses performed by Schnabel Engineering indicate that if the embankment dam breach was to be simply repaired, the existing dam crest would be overtopped by 0.4 feet during the 100-year flood, and by 1.9 feet during the ½ PMF, based on the total available spillway discharge capacity (Schnabel 2016). Possible remediation measures to meet regulatory requirements include raising the embankment dam crest, lowering the normal operating pool, increasing the total spillway discharge capacity, and providing overtopping protection. Additionally, due to the erodible nature of earthen channel spillways, the auxiliary spillways should either be armored or raised to limit operation to floods greater than the 50-year event.

4.3. Gills Creek Watershed

Heritage Engineering is developing preliminary designs to reconstruct Cary's Lake Dam and to repair Spring Lake Dam. Due to the relatively short crest length available for Cary's Lake Dam, and the large design discharge capacity required for the available reservoir head, replacement of the embankment section with a concrete overflow structure is proposed to increased spillway capacity. The existing concrete auxiliary spillways on both abutments would be repaired as required, with repairs including injection grouting at the foundation. The preliminary construction cost estimate for Cary's Lake Dam is $1.25 million. Spring Lake Dam would receive a flatter downstream embankment slope of 4H:1V, with a turf reinforcement mat for overtopping protection, and concrete auxiliary spillway repairs for an estimated construction cost of $350,000 (Creed, 2016).

5. CONCLUSIONS

Record rainfall across South Carolina in October 2015 resulted in numerous embankment dam failures, due primarily to dam overtopping and erosion. Those that survived overtopping may have been saved by high tailwater levels (reducing the differential head on the crest) and by the presence of trees and heavy vegetation (reducing flow velocities and improving erosion resistance). Despite the apparent beneficial effect here of vegetation, trees and dense brush are never recommended at dams due to the potential for internal erosion and piping along root systems, the potential for hydraulic shear stress concentrations at isolated trees during overtopping flow, and the adverse effect on general maintenance and inspection activities. Only one dam had been provided with an overtopping protection system (Forest Lake Dam). At least one dam seemed to avoid overtopping but failed as a result of a localized breach due to apparent internal erosion and piping at a buried conduit (Barr Lake Dam), but nevertheless may have helped cause the subsequent overtopping failure of two downstream dams (Gibson Pond and Old Mill Dams). This historic event exposed serious hydrologic deficiencies for many state-regulated, privately-owned dams. Those dams that survived and those to be rebuilt will be subject to state regulations requiring a much greater level of flood protection for dam safety, depending upon dam size and hazard classification. This could involve significant modifications to increase spillway discharge capacity and to provide dam overtopping protection. Potential funding sources for the necessary modifications to many of the privately-owned dams are yet to be determined. Some of the breached dams may never be rebuilt.

6. ACKNOWLEDGMENTS

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