Geotechnical Observations of Dams Failed During the 2015 Historic Flooding in South Carolina

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ABSTRACT: *This paper presents a description of post-flood reconnaissance and geotechnical investigation of four earthen dams that were breached or damaged following an extreme flooding event in South Carolina in 2015. As a result of unprecedented rainfall and flooding that occurred during a five-day period at the beginning of October in 2015, a total of 51 earthen dams failed and nearly 200 were damaged. Many of these dams failed due to overtopping that led to a breach of the dam. Among the four dams investigated, full breach was observed at three dams; two of which were overtopped, and one was not. The fourth dam was not breached but was severely damaged. For each of these dams, the paper documents background information, pre-flood conditions, post-flood field observations and measurements, and laboratory testing results of collected soil samples. Impacts of vegetation on the dams and the effects of dam failure on critical infrastructure are also presented. The detailed descriptions and geotechnical investigations of the dam failures presented herein serve as case histories that can be used for dam breach modeling and risk assessment of dam failure.*

KEYWORDS: Floods, Earthen Dam, Overtopping, Erosion, Spillway

SITE LOCATION: Geo-Database

INTRODUCTION

In the United States, there are more than 90,000 regulated dams. Of these, approximately 85% are earthen dams according the National Inventory of Dams (USACE 2016). Many of these dams were built for flood protection, recreation, hydroelectric generation, and irrigation purposes. The average age of these dams is over 50 years, and some are older than 150 years (USACE 2016). Aging and deterioration impact the integrity and reliability of the dams to function properly during extreme weather events, which in turn can jeopardize the health and safety of people and property downstream.

An extensive study by Foster et al. (2000) indicated that nearly 94% of the failure mechanisms of earthen dams involved some form of erosion. Nearly 48% of the failures were related to surface erosion due to overtopping and nearly 46% were related to internal erosion or piping failures. Weather events that produce unusually high amounts of precipitation can trigger earthen dam failures due to one or both of these mechanisms. Surface erosion-induced failure usually starts in points of slope

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discontinuity in the downstream side-slope, such as the toe of the dam, with the formation of a "scour hole" that enlarges laterally and moves up the slope until breach occurs (Singh 1996). The "scour hole" could also be formed in the crest of the dam (Chinnarasri et al. 2004; Dupont et al. 2007; Schmocker and Hager 2009) and then expand towards the downstream side-slope. Piping-induced failure, on the other hand, may initiate anywhere in the dam where a crack or defect exists, and where the erosive forces due to seepage could remove soil particles from the dam and the foundation. The erosion of soil particles progresses to form pipes that then increase in diameter until the dam becomes unstable and collapses (Singh 1996; Bonelli 2013).

High-quality data from case histories of dam failures is a major need to develop breach models applicable to both overtopping and piping- or seepage-induced failures. In general, dam breach models combine hydraulic and hydrologic information of the impoundment and the flood event, coupled with geotechnical information of the dam, to develop predictions of failure scenarios, disaster mitigation, damage assessments, characterization of the mechanics of the breach, among others (Singh 1996). The geotechnical information used in these models includes the dimensions of the structure and soil properties, such as the grain size distribution, grain shape, density, and permeability (e.g., Fread 1988; Hanson et al. 2005; Schmertmann 2000; Sellmeijer et al. 2011). Models of overtopping use post-failure information, such as the size and shape of the breach (e.g., Tingsanchali and Chinnarasri 2001; Franca and Almeida 2004). Models of seepage-induced failure typically use pre-failure characteristics because evidence needed to assess internal erosion is lost when the breach occurs (Richards and Reddy 2007; Bonelli 2013). Therefore, it is common to use qualitative comparisons with available case histories (e.g., Fell and Wan 2005), or estimations of erosion indices and potential internal instabilities (e.g., Briaud et al. 2001; Wan and Fell 2004), based on fundamental soil characteristics and soil classification, to assess the development of piping in earthen dams.

Although storm-induced dam failures are not frequent, case histories of such failures are extremely valuable for the civil engineering community and the general public. Froehlich (2008) performed dam breach analysis based on data collected from a total of 74 dam failures. The statistical analysis accounted for physical information of dams and precipitation during flood events to develop a dam breach model used for dam failure prediction. Factors, such as soil characteristics, soil composition, and vegetation, are not considered. Wahl (2010) provided an extensive literature review of embankment dam breach parameters based on data from 108 dam failures. Data including breach width and time of failure were used to predict the peak discharge during the beach. Wahl (2010) also discussed the limitations of conducting full-scale or large-scale testing and highlighted some of the gaps in the existing case studies.

Case studies related to the geotechnical aspects of dam failures due to flooding are limited. GEER (2015) reported one dam failure during the 2015 Central Texas floods. The earth dam located at Bastrop State Park was relatively small (7.3 m high) and impounded a lake with a maximum capacity of 136,000 m^3 when full. The dam was overtopped and a section that was 35 m wide by 7.1 m deep was washed out. No clear evidence of a fine-grained soil (clay) core was observed. Instead, the dam appeared to be constructed of clayey-sandy soils. This was confirmed with soil classification of bulk samples. GEER (2016a) reported several levee failures during the 2015-2016 Midwest floods. Observations included overtopping, internal seepage/erosion, scour, and sand boils. Soil sampling and testing was not part of that study.

This paper presents four case studies of earthen dam failures in South Carolina that resulted from extreme rainfall and flooding in 2015. These case studies are based on a post-flood reconnaissance and geotechnical engineering evaluation that was performed approximately two months after the event. The investigation utilized field observations and measurements, historical inspection reports, communication with dam owners and eyewitnesses, and results from geotechnical testing of soil samples collected from each dam.

BACKGROUND

In South Carolina, there are over 2,400 dams regulated by the South Carolina Dams and Reservoir Safety Program of the South Carolina Department of Health and Environmental Control (SCDHEC) (USACE 2016), and an unknown number of unregulated dams. To be regulated, a dam must meet one of three criteria: (1) measure at least 7.6 m in height; (2) impound at least 62,000 m^3 of water; or (3) have the potential to cause loss of human life if it fails. With a few exceptions, dams in South Carolina are typically considered to be small based on their size and storage capacity (ICOLD 2011). However, approximately 30% of the regulated dams are classified as "high-hazard potential" and "significant-hazard potential" dams, which indicate that dam failure will cause loss of life and property damage. The age of most dams also contributes to the heightened concerns with hazard potential. Nearly 80% of regulated dams were built in the 1970s or earlier (USACE 2016); many of them were built in the early 1900's for agricultural purposes or hydroelectric power generation. The typical spillway design flood criteria effective since 1978 (SCDHEC 2018), ranges from a 50-year flood event up to the Probable Maximum

Flood over the area, depending on the size and hazard potential of the dam. However, since most of the dams in South Carolina are more than 60 years old, records of their design and construction are not available in most cases. Thus, the design criteria for most of the dams in South Carolina are unknown and may be different from the current state of practice.

More than 85% of regulated dams in South Carolina are privately owned, which has also contributed to the lack of knowledge on prudent dam maintenance to ensure proper and safe operations. For example, thousands of dams in South Carolina are pond dams that were originally built for the purpose of water supply and irrigation. Today, many of these ponds are being used for recreational purposes as new housing developments have been constructed around them to meet the demands of population growth. Roads were built on top and downstream of these dams. The responsibility of dam operation and maintenance shifted to the new owners which, in some cases, are the homeowners associations of those communities. Prior to the flood event in 2015, the SCDHEC dam inspection reports indicated that some dams had maintenance and safety issues. The issues included dense vegetation, potential for piping, and deterioration of spillway structures. It is unclear whether these issues were resolved before the flood event.

During the period from October 1st to 5th 2015, the combination of an atmospheric low-pressure system and Hurricane Joaquin caused widespread heavy rainfall in South Carolina that resulted in major flooding from the central part of the state to the coast. Joaquin was a Category 3 hurricane at the time the rains began, but later escalated to a Category 4 (NHC 2016). Over 51 cm of rainfall was measured at some locations, and flooding of over 3 m occurred at several locations. The maximum flood recorded was estimated to be less than 0.2% of the annual exceedance probability corresponding to more than a 500-year recurrence interval (Musser et al. 2016). The consequences of the flooding included loss of life and significant damage to infrastructure systems.

SCDHEC reported that 51 regulated dams were breached after the rainfall began, and hundreds of other dams were damaged (SCDHEC 2016). An estimation of the exact time of failure for each of the dams is unknown but all are considered short-term failures (within hours to few days), rather than long-term failures. After the flood, SCDHEC assessed 652 dams statewide and conducted an engineering review of dams in the Gills Creek and Twelve Mile Creek watersheds near Columbia, South Carolina (HDR 2016a, 2016b; SCDHEC 2016). GEER (2016b) conducted field reconnaissance approximately one week after the flood event and their report provides a description of the rainfall and flood event along with the observations of a dozen dam failures including nine breached dams and two overtopped dams without a breach. The observations of dam failures were based on available information, photographs, and aerial images. Tabrizi et al. (2017) collected data from several of the failed dams and used hydrological modeling to estimate peak discharge, maximum height of overtopping, and maximum reservoir volume behind the dam at the time of failure, among others, and developed a model to predict breach dimensions. The proposed model was compared with other dam breach models and found to be within 30% deviation bounds. The maximum overtopping depth was found to be a critical parameter in their model.

SITE INVESTIGATION METHODS

The four dams studied in this paper were selected based on the differences in failure mechanisms and their accessibility immediately after the flood event and later on different occasions. The dams studied are labelled A, B, C, and D in Figure 1. These sites are located in Richland and Lexington counties, and are within 28 km from Columbia, South Carolina. The sites were first visited after the October 2015 flooding as part of a post-flood reconnaissance to 29 of the 51 failed earthen dams. The four selected dams were then revisited for further investigation.

Dams A, B and C are regulated dams, and information about these dams was obtained from the National Inventory of Dams (USACE 2016). The information included the year the dam was built, purpose, hazard classification, storage capacity and dam dimensions. Historical inspection reports were also reviewed (SCDHEC 2016). Dam D is not a regulated dam, and information about this dam was collected from an engineering report (S&ME, unpublished report, 2011) provided by the dam owner.

Visual inspection was performed to obtain extensive photographic evidence and document descriptive information related to each dam failure, including: (1) soil erosion at the crest, toe and side-slopes of the dam; (2) location and condition of spillways; (3) defects on the crest and upstream and downstream side slopes; (4) presence and extent of vegetation; and (5) condition of the roadway, if present, on the crest or adjacent to the dam. Measurements of the width and length of breach, the crest and side slopes of the embankment, and the dimensions of spillways and adjacent roadways and vegetation, were obtained using a measuring tape and laser distance meter. Dimensions of the embankment that could not be measured in the field, such as height and length, were obtained from the National Inventory of Dams (USACE 2016).

Information collected from visual inspection was used to design a sampling methodology to ideally obtain the most representative samples of different sections of the structures, including the soils in the core, the crest and side slopes, the foundation, and the materials on the breach and damaged zones. However, the sampling plan varied from site to site, based on the local characteristics of the breach, the terrain, the local water level, and access difficulties. Therefore, the sampling plan focused on obtaining samples from the breach, at sites where the breach was accessible, and covering different sections of the dam. In the remaining locations, samples were obtained from the surface of the dam and as near as possible to the breach zone.

Bulk soil samples and Shelby tube samples were collected from 5 to 6 sampling locations at each dam site. The bulk samples were used for soil classification (per ASTM D2487), and the tube samples were used to measure dry unit weight (per ASTM D2937) and coefficient of permeability. The coefficient of permeability was determined using the Constant Head method (per ASTM D2434) in samples with relatively high permeability. A modified Constant Head method test using pressure panels was used in samples with low permeability, with increments of the pressure head ranging from 60 to 400 kPa.

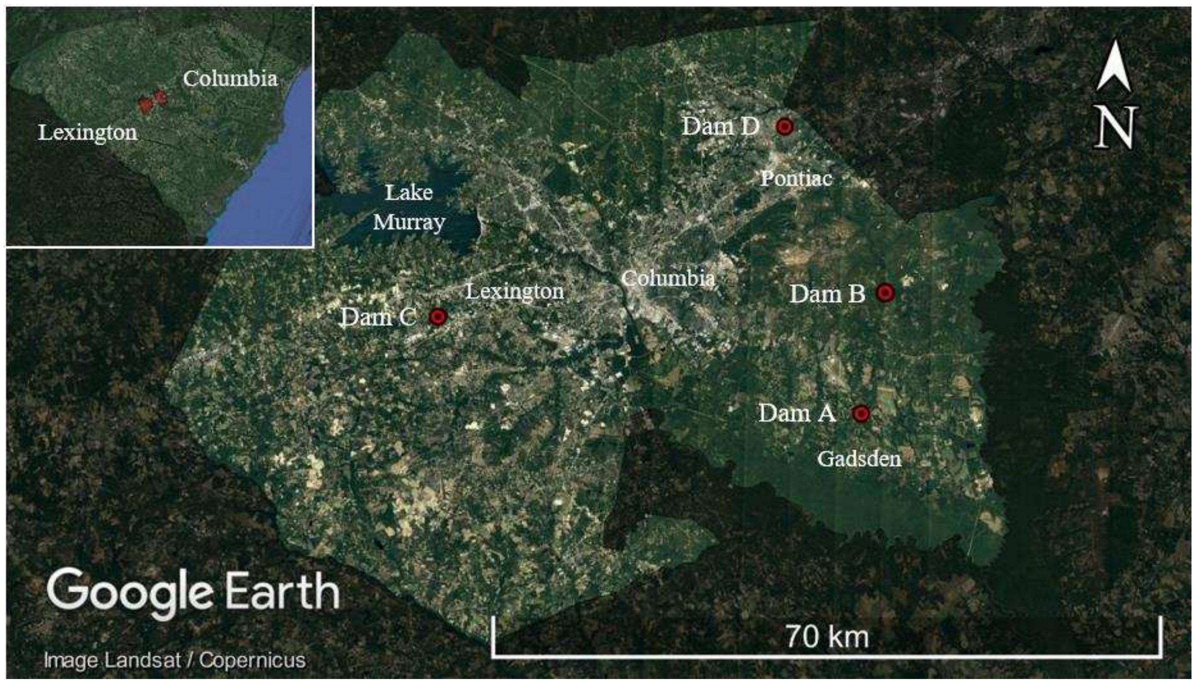

Figure 1. Map showing the locations of the four dam sites in South Carolina (Google Earth, accessed on April 7, 2018).

RESULTS OF SITE INVESTIGATION

The results from the document review and field investigation are presented for the four sites studied. Dams A, B and C, are examples of dams that were fully breached. Dam D is an example of a dam that was damaged, but not breached.

Full Breach Failure

Dam A: Southeastern Region of Richland County

Dam A is located 28 km southeast from downtown Columbia, South Carolina. The dam was constructed around 1932 (USACE 2016). Satellite imagery of the dam before and after failure are shown in Figure 2. The crest width was measured to be 16 m, and the upstream side slope was measured to be 30°. The downstream side slope was completely washed out and could not be measured. According to USACE (2016), the height of the dam is 4 m, which is defined as the vertical distance from the lowest point on the crest to the lowest point in the original streambed. The original length of the dam is approximately 290 m. A two-lane roadway that is 16 m wide (including shoulders) runs along the crest of the dam. The dam impounds a lake with a surface area of about 0.06 km^2 under normal storage conditions (USACE 2016). The dam allows normal and maximum storage capacities of 178,000 m^3 and 400,000 m^3, respectively. SCDHEC (2016) considers this dam to be a low-hazard potential structure (C3) because of the low population density nearby. However, the failure of this dam directly impacted the transportation network because of the roadway on the crest of the dam that served as the State Road S-40-67, a secondary road with Annual Average Daily Traffic (AADT) of 500 and 475, during 2014 and 2015, respectively (SCDOT 2018). As a result of dam failure, the road was removed from the SC State Highway System. The dam is now repaired and is used as a private road (SCDHEC 2016).

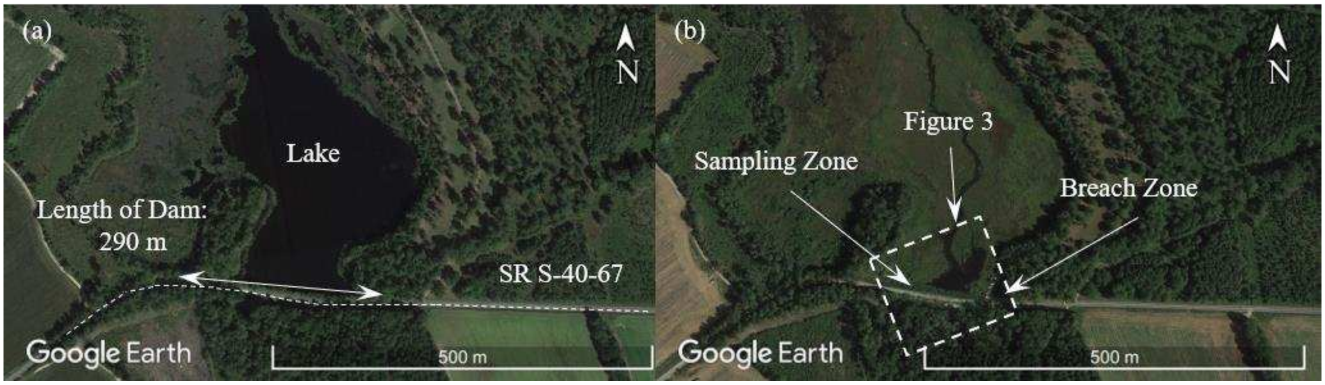

Figure 2. Dam A (a) before and (b) after failure (Google Earth, accessed on April 8, 2018).

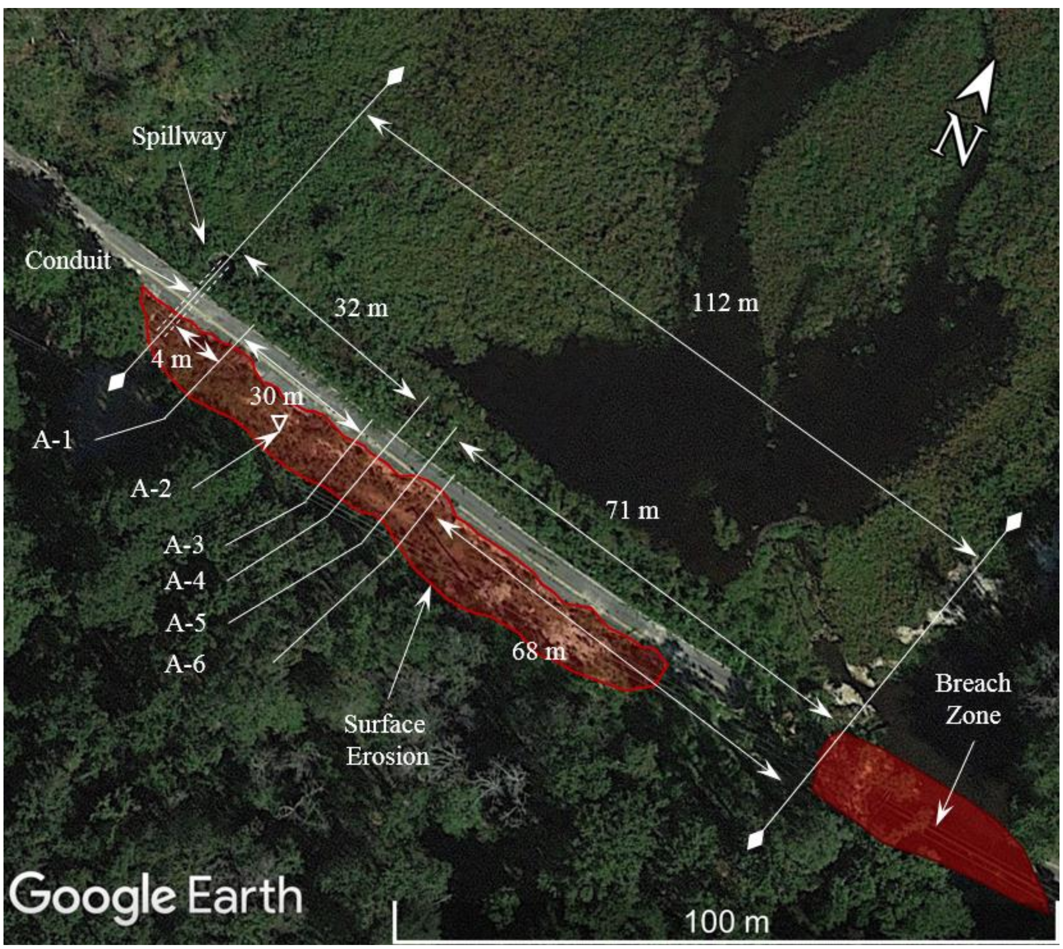

Figure 3. Location of spillway, surface erosion, breach, and sampling locations in Dam A (Google Earth, accessed on April 8, 2018).

The spillway structure of this dam is located on the west side of the dam and about 112 m from the breach zone, as shown in Figure 3. Sampling locations relative to the spillway and the breach zone are also presented in this figure. The spillway is a conduit made of a 1.2 m diameter concrete pipe, as shown in Figure 4a, with a maximum discharge capacity of approximately 17 m^3/s (USACE 2016). The soil above the pipe on the downstream side was washed out, as shown in Figure 4b. It is unknown whether this structure worked as the primary spillway of the dam, or if an additional spillway structure existed before the breach.

Figure 4. Spillway structure for Dam A: (a) conduit on upstream side (north view from SR-40-67), and (b) conduit and washed out soil above on downstream side (north view from downstream).

Vegetation was not present on the crest of Dam A where the road is located. However, there is vegetation on the edges of the crest adjacent to the road and on the upstream and downstream sides of the dam. Mature trees with heights of nearly 12 m were observed on the upstream side, parallel to the road and nearly 3 m away from the upstream shoulder (see Figure 5a). Trees on the downstream side have similar heights, but were found nearly 20 m away from the road (see Figure 5b). All of the mature trees appear to be part of the natural growth in the local ecosystem. It is unclear if the presence of vegetation influenced dam performance or contributed to its failure. In the area where soil was exposed on the downstream side slope (noted as surface erosion in Figure 5b), there were no trees present and no roots observed in the soil. Near the northeast section of the breach, several trees were found tipped over the road (see Figure 6), but no roots were observed in the soil.

Figure 5. Vegetation on Dam A: (a) vegetation upstream and downstream of the dam (east view from S-40-67), and (b) vegetation and surface erosion on the downstream side of the dam (east view from downstream).

Damage to this dam includes a complete breach and a large zone of surface erosion separate from the breach, as shown in Figure 3. The breach is located near to the east end of the dam. The breach extended approximately 50 m of the total 290 m length of the dam, and nearly 7,300 m^3 of material, including soil and pavement, were washed out (see Figure 6). In the breach zone, several trees on the upstream side slope tipped over the road in the direction of water flow (see Figures 6 and 8), which provides some evidence of overtopping. In the surface erosion zone, the soil erosion along the downstream side slope extended over 60 m parallel to and 20 m perpendicular to the road, as shown in Figures 3, 5b and 7b. As shown in Figure 7a, part of the asphalt shoulder and roadway collapsed above the zone of surface erosion.

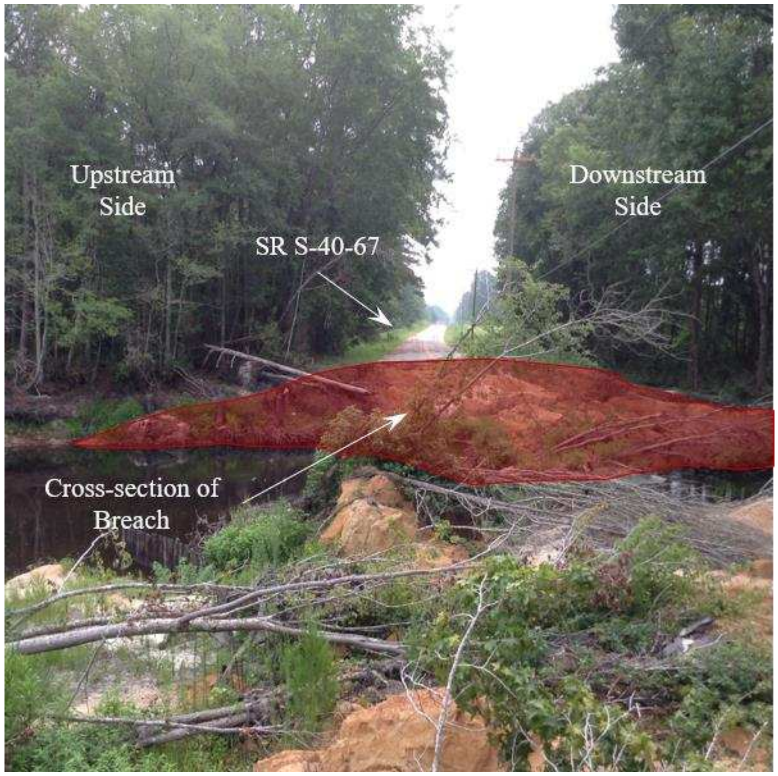

Figure 6. Cross-sectional area of breach in Dam A (east view from SR-40-67).

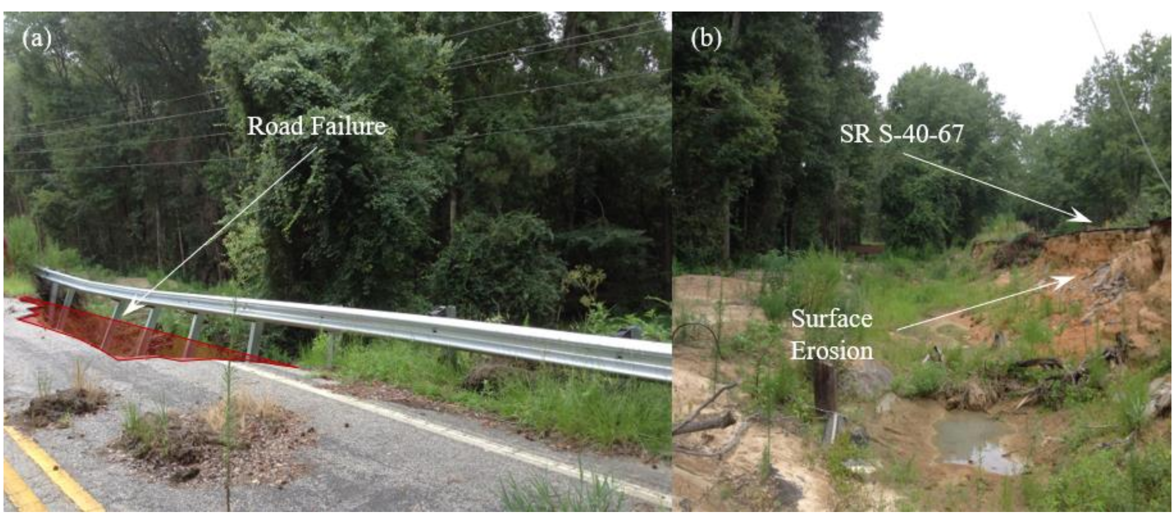

Figure 7. Failure of Dam A: (a) road failure of State Road S-40-67 (southeast view from S-40-67), and (b) surface erosion due to overtopping (west view from downstream).

Laboratory testing results from soil samples collected at six locations from the downstream side slope of the dam are presented in Table 1. Approximately half of the road lane collapsed due to slope failure; therefore, the samples were collected relatively close to the center of the embankment. The samples were obtained in the area where surface erosion and slope failure occurred except for sample A-2, which was obtained from the foundation soil. The distance from the crest of the dam to the sample locations is presented in Figure 9, and the sampling depth for each hole is presented in Table 1. The distance of sampling locations relative to the breach zone are shown in Figure 3. The dam materials are mostly silty to clayey sands with 23% to 42% low plasticity fines. The foundation soil (A-2) at a depth of approximately 56-81 cm also appears to be silty sand. Based on these test results and the visual field observations of the soils along the length of the exposed embankment, the dam material appears to be relatively consistent (SM or SC) with no definable core. The coefficient of permeability is low to very low (10^{-4} to 10^{-6} cm/s). Based on the soil characteristics in Dam A, internal erosion would occur moderately to extremely rapidly in the presence of cracks or hydraulic fractures (Wan and Fell 2004).

Table 1. Summary of laboratory testing of soil samples collected from Dam A.

Sample Location	Sampling Depth (cm)	Soil Classification[1]	Soil Plasticity[1]		Fines Content[1] (%)	Dry Unit Weight[2] (kN/m³)	Coefficient of Permeability[2] (cm/s)
			PI	LL			
A - 1	42 – 67	SC	8	28	42	17.1	10^{-6}
		SC	12	29	42		
A - 2[3]	56 – 81	SM	1	15	29	18.1	10^{-4}
		SM	3	17	27		
A - 3	33 – 58	SM	7	32	37	17.6	10^{-5}
		SM	11	39	38		
A - 4	71 – 97	SC-SM	4	20	24	N/A	N/A
		SC	15	25	23		
A - 5	41 – 66	SM	NP[4]	14	23	N/A	N/A
		SM	4	15	22		
A - 6	25 – 51	SM	10	36	43	18.6	10^{-4}
		SC	15	35	41		

[1]Obtained from testing two specimens from bulk samples.
[2]Obtained from tests performed on tube samples. Note that the Constant Head method is valid for soils with fines contents lower than 10%.
[3]Sample obtained from foundation soil.
[4]Non-plastic soil.

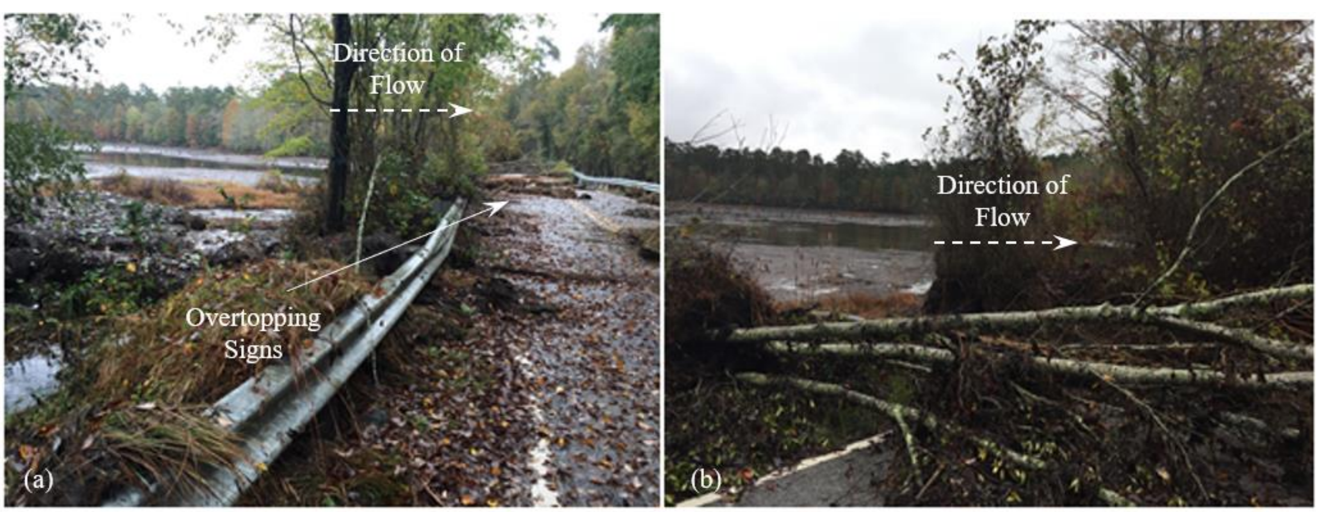

Figure 8. Evidence of overtopping during the flood for Dam A: (a) eroded vegetation and debris on the crest (east view from SR-40-67); and (b) fallen trees on the crest (north view from SR-40-67).

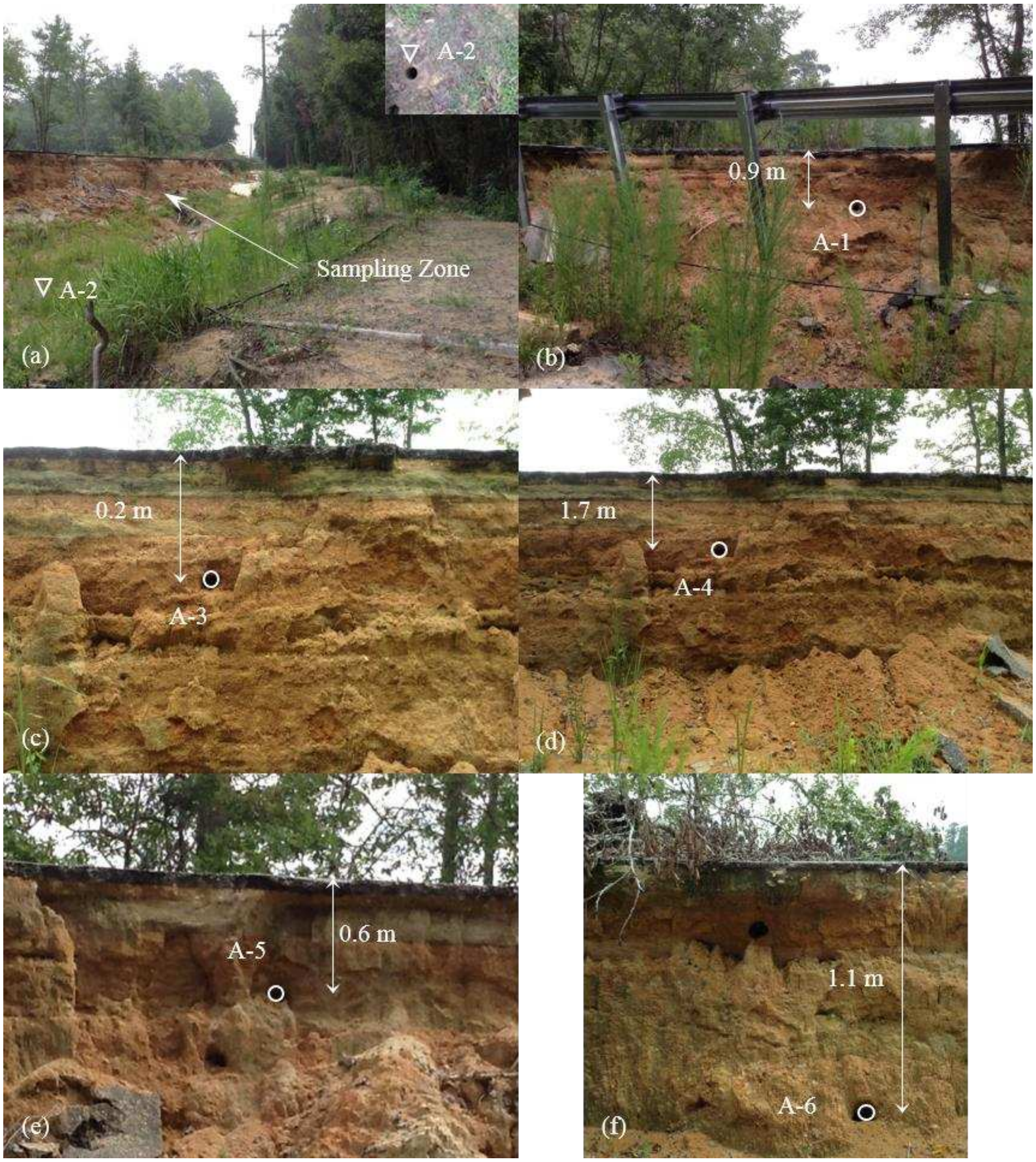

Figure 9. Sampling locations in Dam A: a) east view from downstream side, and b), c), d), e) and f) north view from downstream side (∇: vertical sample, O: horizontal sample).

Dam B: Central Eastern Region of Richland County

Dam B is located 27 km east of downtown Columbia, South Carolina. The dam was constructed in 1960 (USACE 2016). Satellite imagery of the dam before and after failure are shown in Figure 10. The crest width of the dam was measured to be 6 m and the upstream side slope was measured to be 23°. The downstream side-slope was not measured due to slope failure caused by surface erosion. According to USACE (2016), the height of the dam is 4.3 m, and the original length of the dam is approximately 130 m. The dam impounds a lake with surface area of 0.08 km^2 under normal storage conditions. The normal and maximum storage capacities are 89,000 and 166,000 m^3, respectively. SCDHEC (2016) considers this dam to be a significant-hazard potential structure (C2). Several houses are located on the upstream and downstream sides of the dam (see Figure 10a). The dam is located west of Congress Road, a two-lane road located 40 m downstream of the dam. Pictures of the breached section of the dam, looking toward Congress Road are shown in Figure 11. The dam breach washed out both lanes of Congress Road and damaged the bridge supporting the road, as shown in Figures 12 and 13.

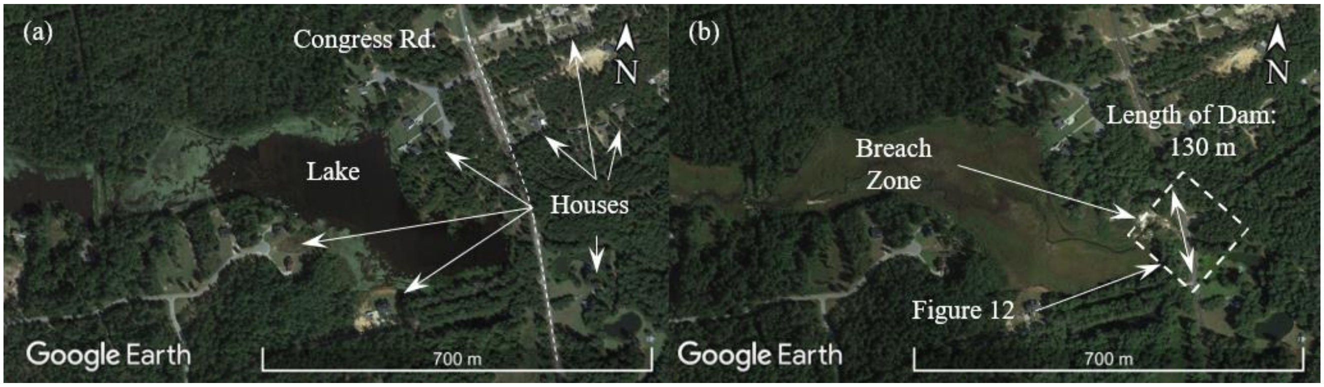

Figure 10. Dam B (a) before and (b) after failure (Google Earth, accessed on April 8, 2018).

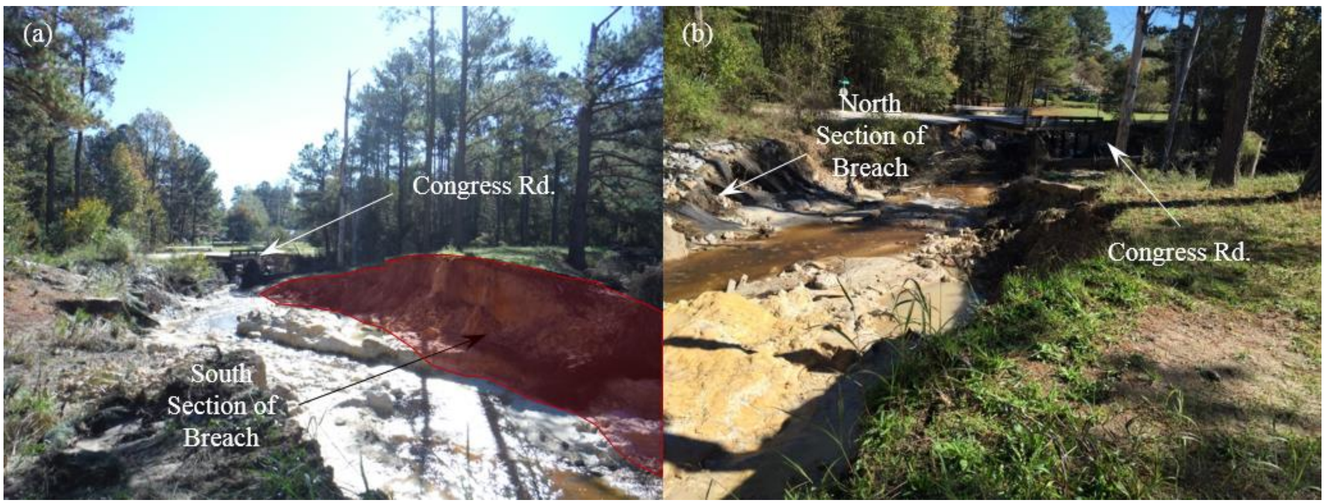

Figure 11. Breach section in Dam B: southeast views from (a) the north section of breach and (b) the south sections of the breach.

Two spillway systems were observed at Dam B, but it is unknown which worked as primary spillway before the breach. According to USACE (2016), the maximum discharge capacity of the dam was approximately 34 m^3/s. The first system was located on the west side of the dam, nearly 24 m from the breach zone (location marked in Figure 12). It is composed of a 1.3 m wide concrete inlet structure leading to a 1.2 m diameter concrete discharge pipe (see Figures 14a, 14b and 14c). A pulley lift system is attached to a metal frame surrounding the concrete. The structure appeared to be missing a sliding door that would have been raised and lowered with the pulley to manually control the lake water level. Water from the lake was observed draining through the pipe on the downstream side of the gate (see Figures 12 and 14c). The second spillway was found near the south section of the breach. It consisted of a corrugated-metal riser pipe supported by a concrete base. The dimensions of the conduit were not measured. As shown in Figure 14d, this structure appears to be damaged, displaced, and separated from a conduit that would have been used to drain water from the lake, presumably through or under the dam, towards a creek flowing below the Congress Road bridge (see Figure 12). According to an SCDHEC inspection report from 2008 (SCDHEC 2016), repair procedures were required in the corrugated-metal riser pipe as well as calculations assuring that the spillway met design flood requirements according to the hazard potential. It is unknown whether the spillway was repaired before the flood event.

Vegetation was observed over the entire surface of the dam (see Figure 15). The upstream side-slope and crest of the dam are covered with grass and shrubs with heights less than 1 m. Several mature trees with heights from 15 to 18 m were observed on the crest and downstream side-slope of the dam (see Figures 15a and 15b). The roots of one of these trees were exposed by the dam breach, as shown in Figure 15c. The roots reach depths of nearly 2.5 m, penetrating through the upper half and into the lower half of the 4.3 m high dam. The SCDHEC inspection report from 2008 (SCDHEC 2016) also highlighted the need of removing vegetation to an acceptable grass cover. It is clear that the vegetation was not removed, as requested.

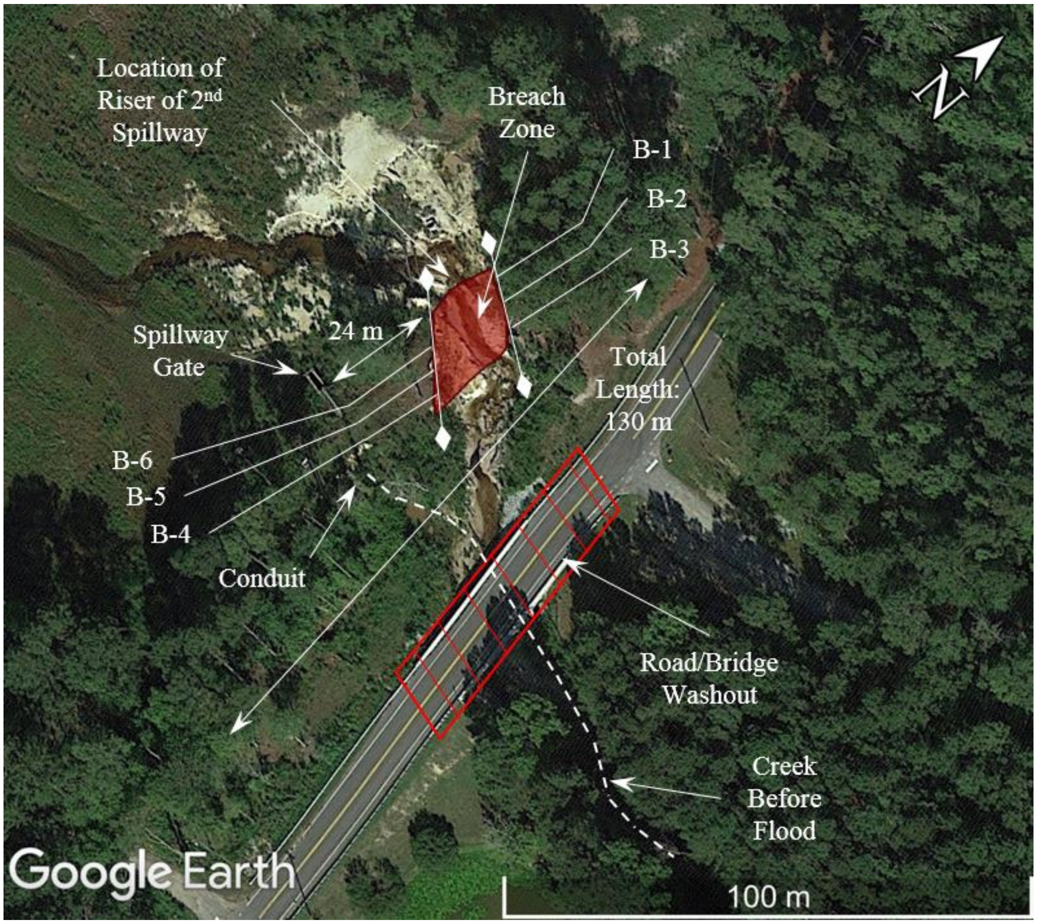

Figure 12. Location of spillways and breach in Dam B (Google Earth, accessed on April 8, 2018).

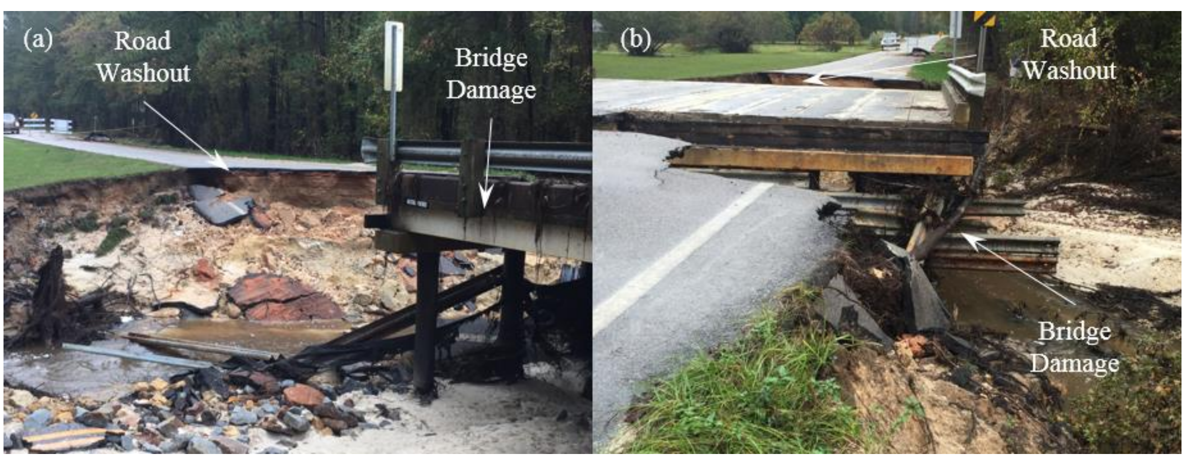

Figure 13. Congress Road and bridge damage: a) northeast view from west shoulder, and b) north view from east shoulder.

The dam was completely breached during the flood as shown in Figure 11. The location of the breach (see Figure 12) was close to the north end of the dam and close to the supposed original location of the second spillway riser pipe. The breach was approximately 15 m of the total 130 m length of the dam. Nearly 1,050 m^3 of embankment material was washed out during the flood event. Surface erosion was observed along the downstream side slope extending along the entire length of the dam, as shown in Figure 16. Trees on the downstream side slope of the dam were partially or fully tipped over and some appeared to be displaced (Figure 15b). These observations might indicate overtopping of the dam.

Figure 14. Spillway structures in Dam B: (a) location (view along the crest looking north), (b) concrete spillway gate (east view from upstream), (c) discharge pipe downstream from gate (east view from downstream), and (d) failed riser (northwest view from breach).

Figure 15. Vegetation on Dam B: a) low grasses and small bushes on the dam crest, trees on downstream side slope (south view from crest), (b) tipped over trees near breach and zone of surface erosion (west view from downstream), and c) presence of roots throughout the dam on the south breach wall (south view from breach).

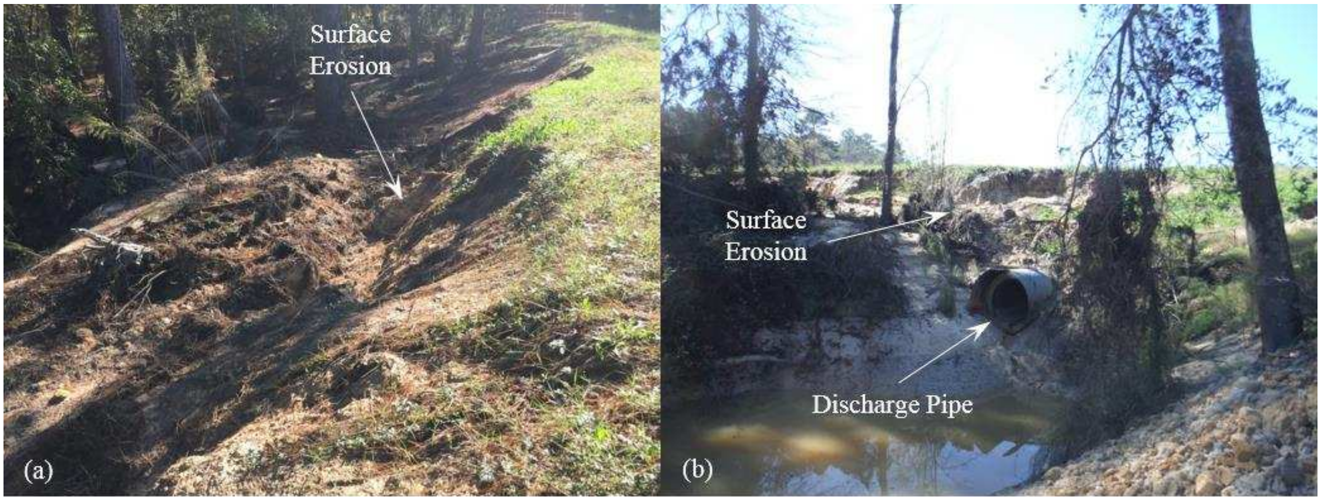

Figure 16. Surface erosion on downstream side slope of Dam B: a) south view from the crest of dam and b) west view from downstream.

Laboratory testing results from soil samples collected at six locations from the breach section of Dam B are presented in Table 2. The sampling locations were selected to acquire soils representative of the full cross-section of the dam. Figure 17 shows the sampling locations viewed from the crest of the dam. The locations relative to the spillway, Congress Road, and the dam length, are also shown in Figure 12. Soils collected from the north and south sides of the breach are different. Samples B-1 and B-3 collected from the north side of the breach are classified as low to high plasticity clays and silts (MH and CH, and ML and CL, respectively), while the remaining soil samples were classified as silty or clayey sands (SM or SC). It is possible that because samples B-1 and B-3 were obtained from the north end of Dam B, there were natural materials scattered among the dam fill, or two different material types were used in the construction of the dam. In either case, there was no evidence of a dam core. Based on the results of samples taken closer to the middle section of the dam (B-4, B-5, and B-6), the dam material is mostly clayey sand with low plasticity fines. The fines content ranges from 15% to 49 %. The erosion rate, based on the characteristics of the soils in this dam, is moderately rapid (Wan and Fell 2004). The presence of roots through the dam may result in significant increments of the erosion rate.

Table 2. Summary of laboratory testing of soil samples collected from Dam B.

Sample Location	Sampling Depth (cm)	Soil Classification[1]	Soil Plasticity[1]		Fines Content[1] (%)	Dry Unit Weight[2] (kN/m^3)	Coefficient of Permeability[2] (cm/s)
			PI	LL			
B - 1	14 – 39	MH	31	86	96	15.8	10^{-5}
		CH	52	87	97		
B - 2	< 130	SM	15	42	43	16.5	10^{-5}
		SM	26	60	41		
B - 3	38 – 63	ML	7	30	57	18.2	10^{-5}
		CL	13	28	58		
B - 4	< 130	SC	29	48	18	17.2	10^{-4}
		N/A	N/A	N/A	15		
B - 5	< 130	SC-SM	4	23	25	18.2	10^{-6}
		SC	10	25	24		
B - 6	< 130	SC	12	32	49	18.2	10^{-5}
		SC	14	32	48		

[1]Obtained from testing two specimens from bulk sample.
[2]Obtained from tests performed on tube sample. Note that the Constant Head method is valid for soils with fines contents lower than 10%.

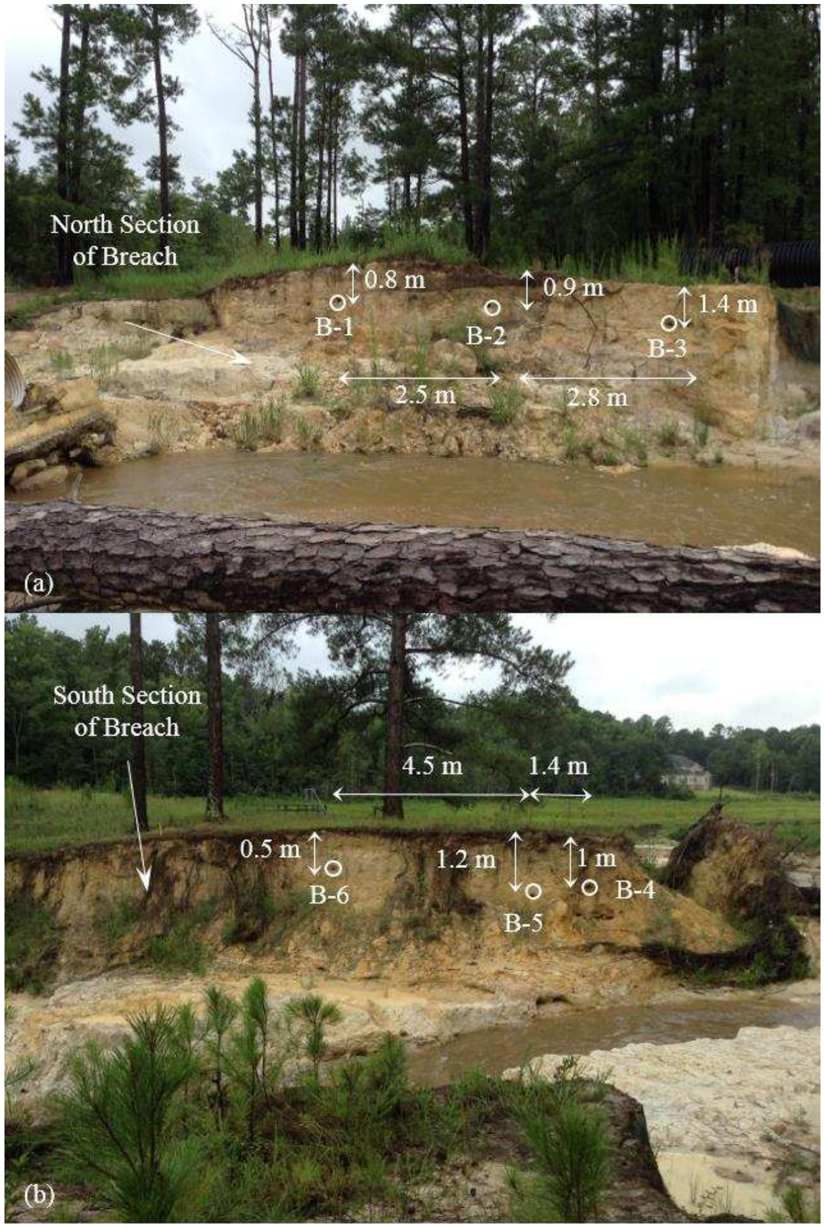

Figure 17. Sampling locations for Dam B, (a) north wall of breach section (north view from crest), and (b) south wall of breach section (south view from crest).

Dam C: Central Region of Lexington County

Dam C is located 21 km west from downtown Columbia, South Carolina. The dam was constructed in 1900 and is one of the oldest dams in South Carolina (USACE 2016). Satellite imagery of the dam, before and after the flood event, are shown in Figures 18a and 18b. The dam was built across a creek, nearly 4 km upstream of two pond dams (labeled Dam E and Dam F in Figure 18c). The crest width of the dam was measured to be 4 m and the upstream and downstream side slopes were measured to be 32° and 35°, respectively. According to USACE (2016), the height of the dam is 4 m, and the original length of the dam is approximately 191 m. The dam is located nearly 130 m southwest from a two-lane state road (labeled Wildlife Road in Figure 18), and close to a new subdivision located to the west of the dam. Dam C impounds a lake with an approximate surface area of 0.26 km^2 under normal storage conditions, allowing a storage of approximately 443,000 m^3. SCDHEC (2016) considers this dam to be a significant-hazard potential structure (C2). Fortunately, the breach did not cause significant damage to Wildlife Road or the houses nearby.

Figure 18. Dam C (a) before and (b) after failure, (c) locations of Dams E and F downstream of Dam C (Google Earth, accessed on April 8, 2018).

Two spillway systems were found at Dam C as shown in Figure 19. According to USACE (2016), the dam has a maximum discharge capacity of 30 m^3/s. One of the systems was observed in the middle of the dam (see Figures 20a) and is a spillway gate made of concrete with a length of approximately 9.5 m. The size of the opening in this spillway gate was nearly 2.5 m in width and 9.5 m in height. The spillway system includes a 10 m x 12 m x 8 m (height x width x length) concrete structure located next to the gate (see Figure 20b). The purpose of this structure is unknown, but it was presumably used for power generation according to the dam owner. The second structure, a spillway gate made of concrete, wood and steel beams (see Figures 20c and 20d), and with a length of approximately 12 m, was found toward the east end of the dam. The opening of this spillway gate was nearly 10 m in length and 2 m in height. Both spillway gates appeared to be in good condition with no observed damage from the flood event. This is expected since the breach zone is 46 m away from the first spillway and 107 m away from the other (see Figure 19). It is unknown whether the spillways worked as primary or emergency drainage systems, or if they were functioning properly before the flood event.

Grass and shrubs with heights up to 1 m were observed over the surface of Dam C (see Figure 21). Mature trees with heights of nearly 15 m were also observed in the area between the downstream toe of the dam and the road (see Figure 21a). Vegetation on the downstream side appears to be part of the natural ecosystem of the area (see Figure 20 and 21a). Roots growing through the dam were exposed in the breach zone (see Figure 21b), with depths of nearly 3.5 m penetrating into the 4 m height of the dam. According to a 2010 SCDHEC inspection report (SCDHEC 2016), vegetation on the downstream side should have been removed to allow inspection of the dam. An inspection report from 2014 indicates that vegetation was partially cleared from the dam, but the presence of trees on the downstream side should have been evaluated for seepage problems. The condition of the vegetation in the crest and side slopes of the dam, before and by the time of the flood event, is unknown.

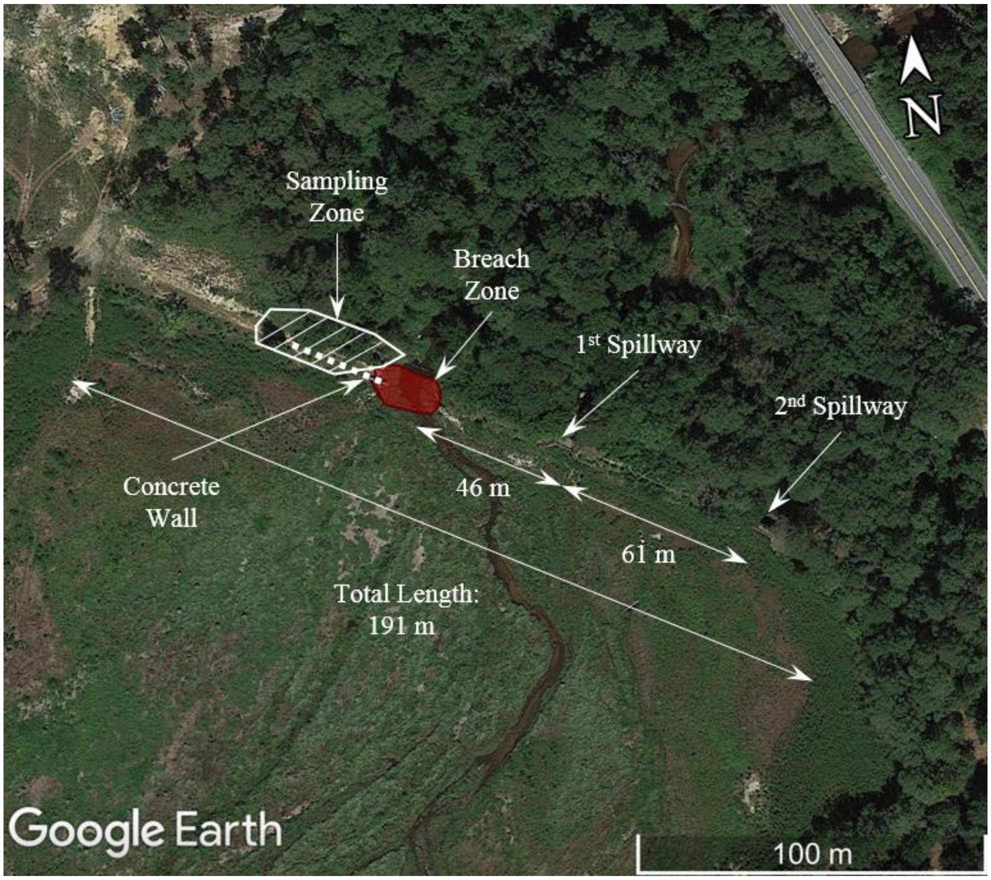

Figure 19. Locations of the breach and the two spillways in Dam C (Google Earth, accessed on April 8, 2018).

Figure 20. Spillways in Dam C: (a) first spillway structure (southwest view from downstream), (b) close up of concrete gate in first spillway structure (southwest view from downstream), (c) second spillway structure near the southeast end of the dam (southeast view from crest), and (d) southeast view of second spillway structure from downstream.

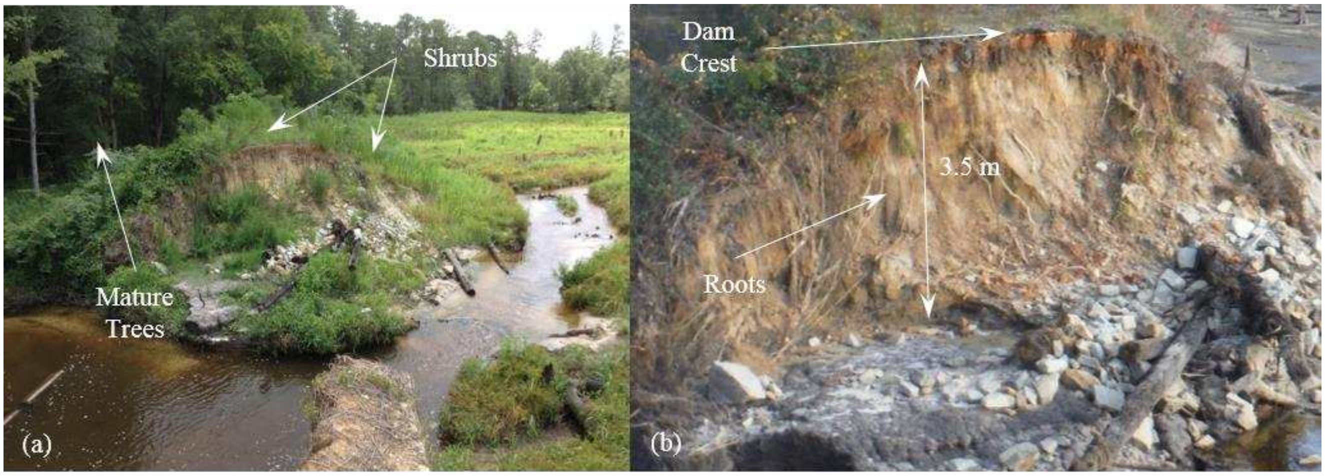

Figure 21. Vegetation on Dam C: southeast views from crest of a) crest of dam with tall grasses and small shrubs (taken 10 months after breach), and b) exposed deep root structures at southeast breach wall (taken 1 month after breach).

The dam was completely breached during the flood event as shown in Figure 22. The breach was located near the middle of the dam, 46 m northwest from the location of the first spillway gate (see Figure 19). The length of the breach was approximately 20 m of the total 191 m length of the dam, and nearly 900 m^3 of soil were washed out. Eyewitnesses during the flood event indicated that overtopping did not occur. Subsequent field observations did not find evidence of surface erosion on the downstream side slope or near the spillways.

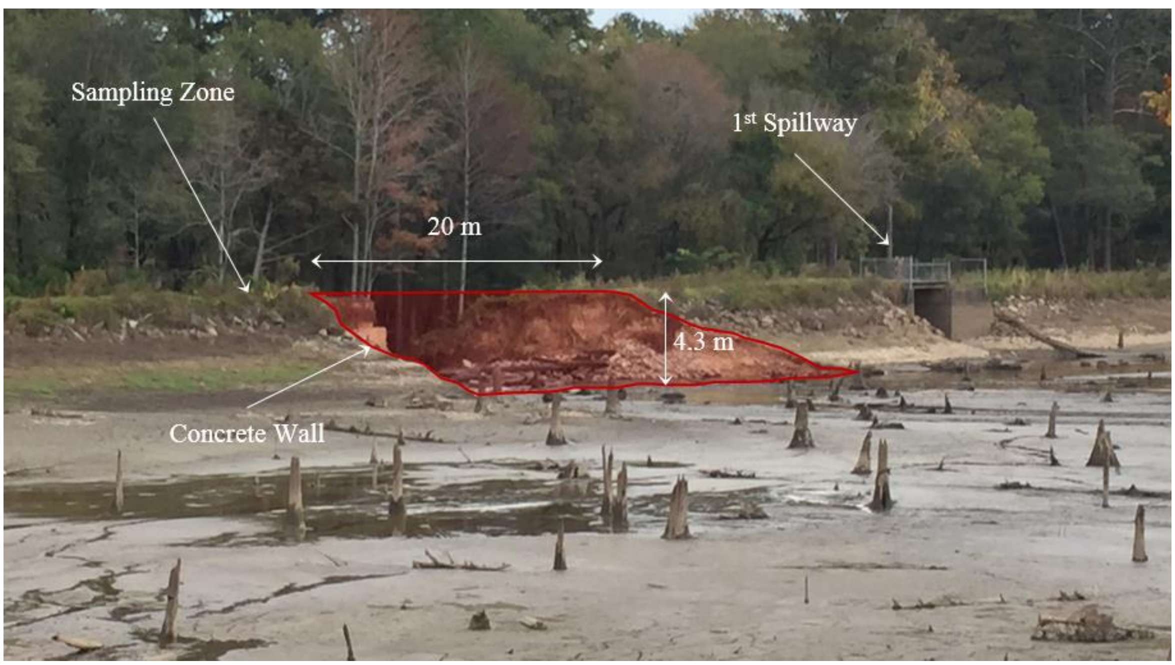

Figure 22. Picture of the breached section of Dam C (northeast view from subdivision). Drained pond in the foreground.

A concrete wall about 4 m high and 0.5 m thick (see Figure 23) was observed at the location of the breach (see Figures 19 and 22). The wall appears to run parallel to the dam crest, within the upstream side slope, but does not extend the entire length of the dam. The purpose of this structure, the actual dimensions, and whether the wall was built before or during the construction of the dam, are unknown. As shown in Figure 23, soil near the wall was washed away during the flood event. According to a SCDHEC inspection report from 2014 (SCDHEC 2016), part of the wall protruded from the dam and had an attached fence that was used as a fishing fence. This fence was no longer attached to the wall at the time of the reconnaissance. The inspection report also highlighted several signs of deterioration in the dam including cracks in the spillway structures and animal burrows. It is possible that internal erosion near the concrete wall initiated the breach of the dam. Cracks in the wall or gaps between the wall and the surrounding soil due to animal activity may result in concentrated flow initiating internal erosion (Bonelli 2013).

Laboratory testing results from soil samples collected at six locations from the crest and downstream side slope of Dam C are presented in Table 3. The sampling locations are presented in Figures 19 and 24. Dam fill materials are mainly clayey to silty sands with approximately 27% to 53% low plasticity fines. Based on the experimental results and field observations of the cross-section of the breach (see Figure 21), the dam fill materials are relatively consistent and a definable core was not observed. The erosion rate, based on the characteristics of the soils in this dam, is moderately to extremely rapid (Wan and Fell 2004).

Table 3. Summary of laboratory testing of soil samples collected from Dam C.

Sample Location	Sampling Depth (cm)	Soil Classification[1]	Soil Plasticity[1]		Fines Content[1] (%)	Dry Unit Weight[2] (kN/m^3)	Coefficient of Permeability[2] (cm/s)
			PI	LL			
C - 1	97 – 122	SC	10	26	28	16.4	10^{-4}
		SM	1	22	N/A		
C - 2	3 – 28	ML	9	47	53	N/A	N/A
		SM	5	42	41		
C - 3	102–127	SC-SM	5	23	29	16.1	10^{-5}
		SC-SM	7	26	30		
C - 4	119–145	SC-SM	6	26	36	18.3	10^{-6}
		SC-SM	7	22	38		
C - 5	102–127	SM	NP[3]	26	27	15.5	10^{-6}
		SM	8	26	29		
C - 6	25 – 51	SC-SM	4	26	32	16.1	10^{-5}
		SC-SM	5	26	27		

[1]Obtained from testing two specimens from bulk sample.
[2]Obtained from tests performed on tube sample. Note that the Constant-Head method is valid for soils with fines contents lower than 10%.
[3]Non-plastic soil.

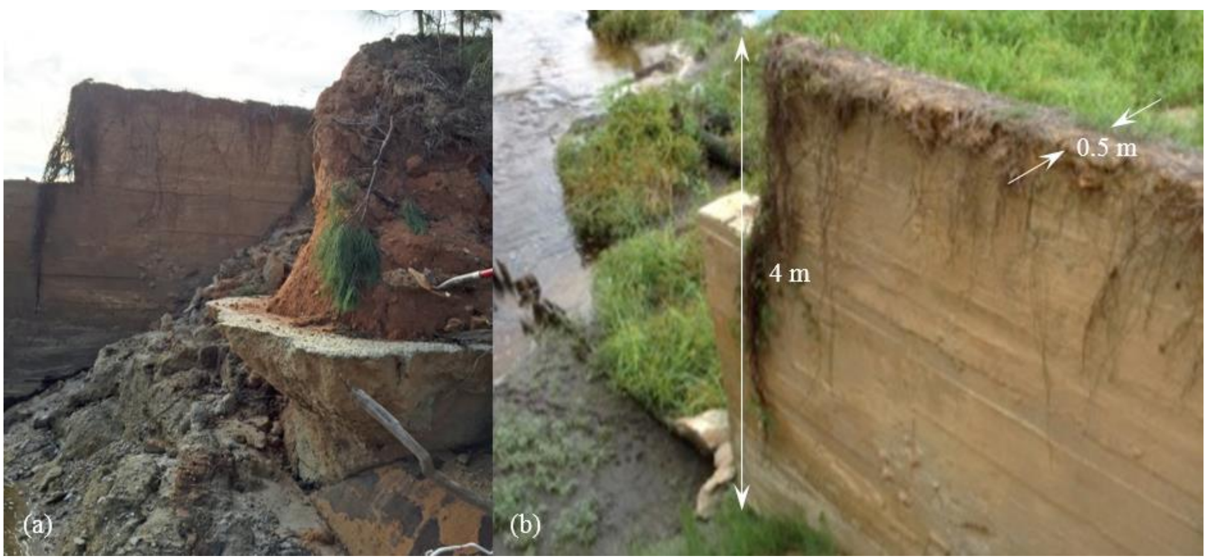

Figure 23. Concrete wall in the upstream section of Dam C, next to the breach zone: a) southwest view from downstream, and b) southeast view from crest of dam.

Figure 24. Sampling locations for Dam C: a) northwest view from southeast section of breach, and b) southwest view from downstream (∇: vertical sample, O: horizontal sample).

Damaged: No Breach Failure

Dam D: Northeastern Region of Richland County

Dam D is located 22 km northeast from downtown Columbia, South Carolina. The dam is not regulated by SCDHEC and the year of construction is unknown. However, based on information provided by the owners, it is assumed to be at least 25 years old. The dam was constructed before the development of a nearby subdivision and has been used to maintain a recreational pond for neighboring communities. Satellite imagery of the dam is shown in Figure 25. Figure 26 presents photographs of the downstream side slope of the dam before and after the flood event. Sloughing in the downstream side-slope occurred before the flood event, as observed in Figure 26a, suggesting saturation of the soil near surface as a result of internal seepage. The crest width was measured to be 4 m, the height of the dam was measured to be 3.7 m, and the upstream and downstream side slopes were measured to be 26° and 23°, respectively. The length of the dam was measured to be 80 m. A two-lane road (labeled Legion Drive in Figure 25b) is located nearly 40 m east and runs parallel to the length of the dam. Many houses are located both upstream and downstream of the dam. Dam D is considered to be a small dam because it impounds a pond with an estimated surface area of 6,900 m^2 and an estimated storage of nearly 8,000 m^3 (ICOLD 2011). These values were estimated from satellite imagery via Google Earth (accessed on September 14, 2016) and information provided by the dam owners. As shown in Figure 25b, water is conducted from the impoundment towards a larger lake located downstream. Dam D was not breached during the 2015 flood event, but was severely damaged. No repairs have been made to date, and based on communication with the dam owners, it is likely that the dam will be removed due to high repair cost.

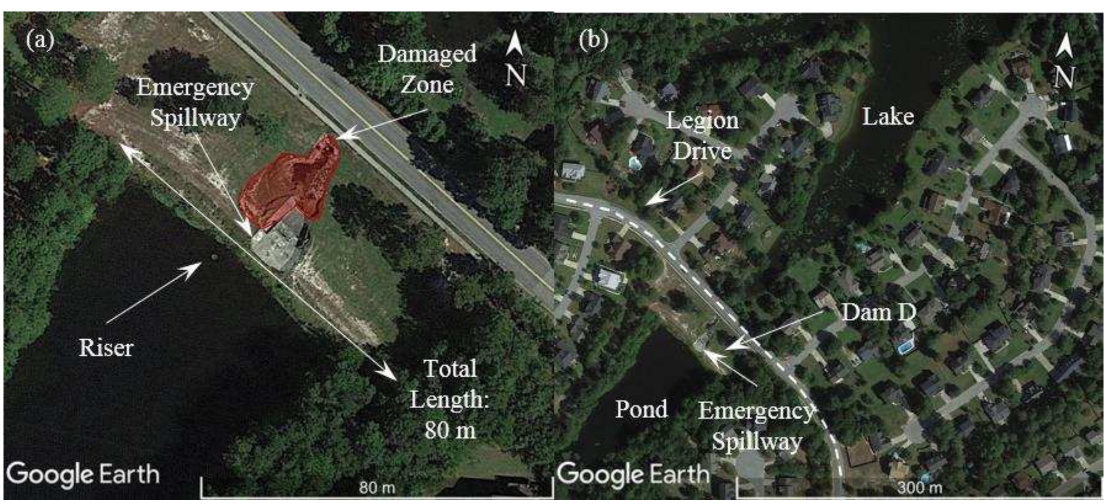

Figure 25. Aerial views of Dam D: a) geometry, draining structures, and damaged zone, and b) location relative to surrounding community (Google Earth, accessed on April 8, 2018).

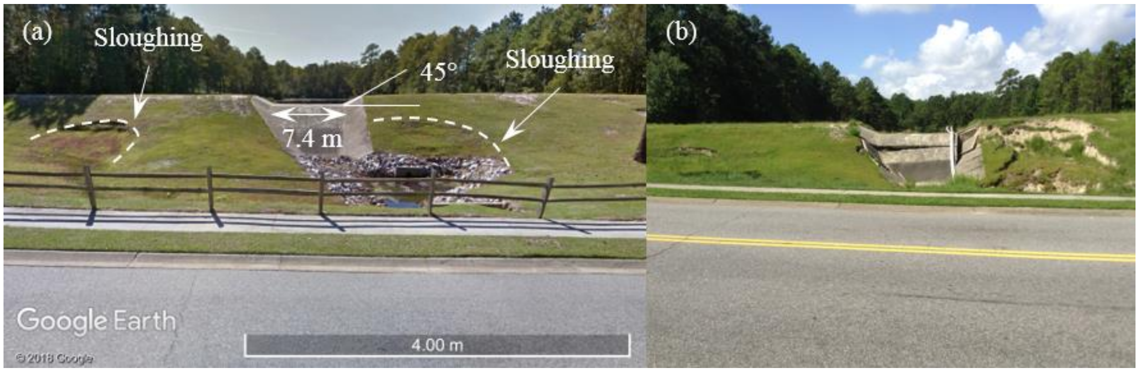

Figure 26. Southwest views of downstream side of Dam D, from Legion Drive: (a) before (Google Earth accessed on January 27, 2016) and (b) after 2015 flood event.

Two spillway systems were found at Dam D. The primary spillway is composed of a corrugated-metal riser used as an inlet (see Figure 27a), and a conduit made of a 0.6 m diameter concrete pipe used as an outlet (Figure 27b). The inlet is located nearly 10 m west of the crest of the dam, while the outlet is located at the toe of the downstream side slope. The second spillway is an emergency (overflow) spillway made of a trapezoidal-shaped concrete channel located in the middle of the dam (see Figure 28). The channel is 7.4 m in length at the base and has side slopes of nearly 45° (see Figure 26). From the photograph in Figure 26a (taken in October 2014), the concrete spillway appears to have been in good condition prior to the heavy rainfall event. After the event, two additional 10 cm diameter PVC pipes were installed on the emergency spillway to lower the water level in the pond (Figure 28a and 28b). All discharge water is directed toward a 1.5 m concrete culvert pipe located below Legion Drive that drains to the lake located downstream (see Figure 25b and 28b).

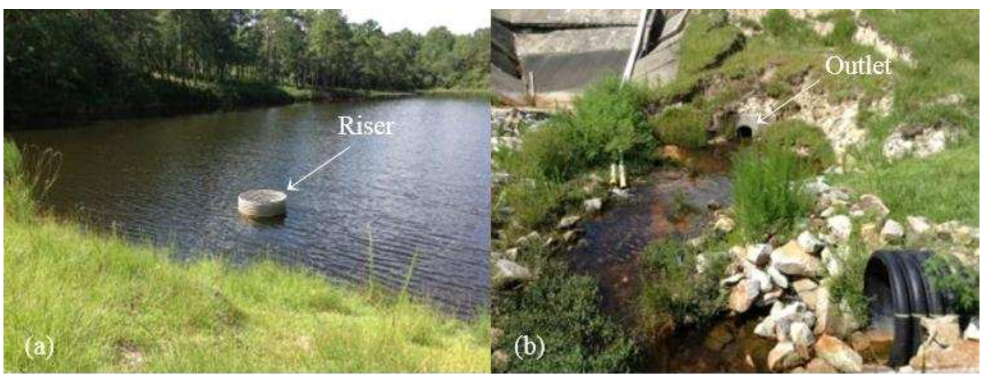

Figure 27. Primary spillway in Dam D: a) riser structure (southwest view from crest); and b) outlet pipe (southwest view from downstream).

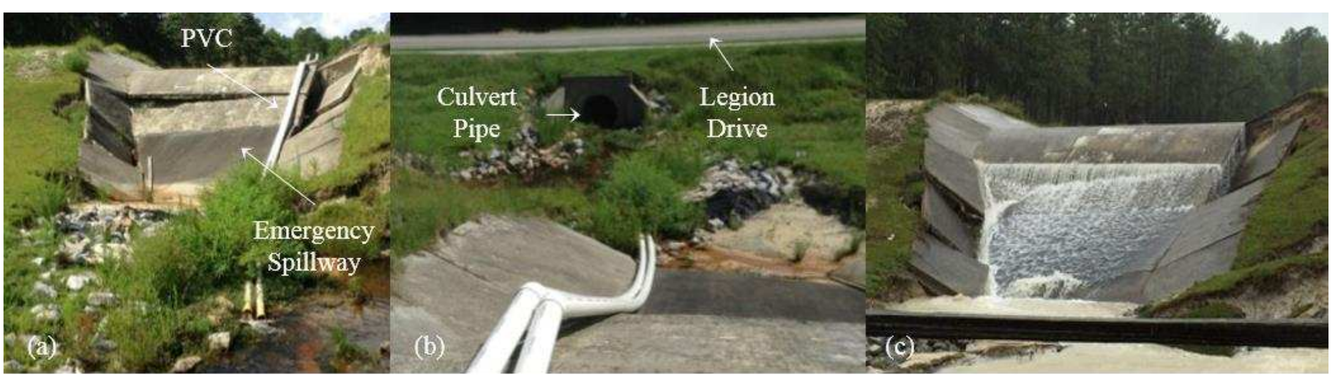

Figure 28. Emergency spillway and PVC drainage pipes at Dam D a) southwest view from downstream; (b) culvert pipe below the two-lane road (northeast view from the crest); and (c) failed concrete spillway during the heavy rain event (southwest view from downstream).

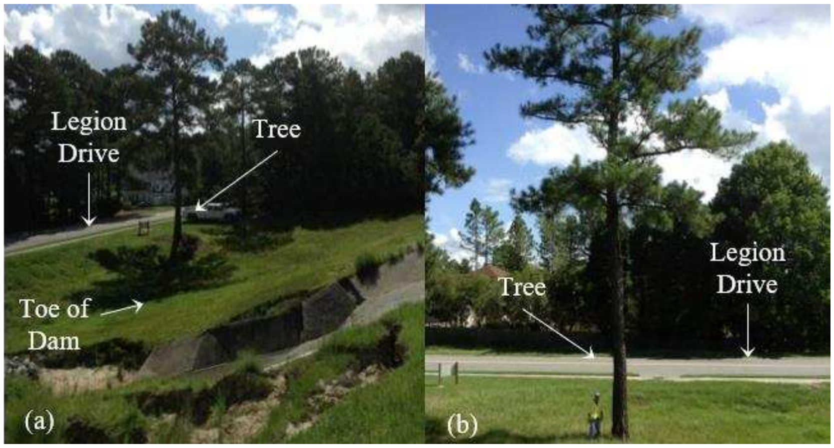

Figure 29. Vegetation on Dam D: a) east view from the crest showing short grasses and trees growing along the roadway near the downstream toe of the dam, and b) north east view from the crest showing a tree near the roadway on the southeast end of the dam.

Dam D did not breach during the flood event but was severely damaged. A shallow slope failure, which was observed to be 15 m in length and 9 m in width, developed adjacent to the emergency spillway (see Figure 30a). The scarp of the slide indicates a vertical displacement of nearly 1 m. Right next to the slide, the concrete panels for the emergency spillway were detached and displaced from the side of the channel. Some cracks were observed in the concrete panels and there were voids between the panels and the soil beneath them. These voids (see Figure 30b) are evidence of erosion at the interface between the base of the concrete slabs and the supporting soil. While the specific mechanism(s) cannot be determined from the visual evidence, field observations and information provided from an eyewitness indicate that the crest of the dam was not overtopped. Thus, erosion was most likely caused by either surface water or subsurface water flow at sufficiently high velocity to undermine the soil support. The undermining and displacement of concrete panels may have contributed to the the shallow slope failure. Furthermore, a high volume of high velocity water flowing over the emergency spillway could have diverted onto the downstream side slope, enhancing the erosion in this area. Surface erosion was also observed near the toe of the downstream side slope where the primary and emergency spillway systems converge (see Figure 27b).

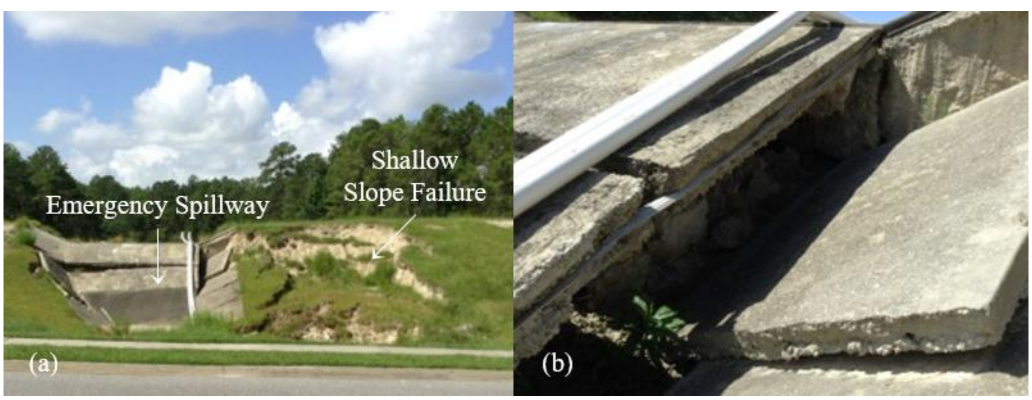

Figure 30. Failure of Dam D: (a) shallow slope failure in the downstream side slope and damage to the emergency spillway (southwest view from Legion Drive), and (b) close up view of voids under concrete slabs due to erosion below the slabs.

The crest of the dam and the upstream and downstream side slopes, except for the concrete emergency spillway, are covered by grass with height approximately 0.1 to 0.2 m (see Figure 29). Otherwise, there was minimal intrusive vegetation observed over the surface of the dam. Six mature trees with heights between 10 and 18 m were observed downstream, between the toe of the dam and the road. Trees were not observed to be growing on the dam and roots were not visible within the failure zone.

Laboratory testing results from soil samples collected at five locations on the dam are presented in Table 4. Sampling locations included the crest of the dam, the upstream side slope northwest and southeast of the emergency spillway, and the sliding zone adjacent to the emergency spillway. Even though sample location D-5 is expected to be closer to the core of the dam (see Figure 31), pre-failure information provided by the dam owner indicates that Dam D does not have a definable core. In fact, the dam fill materials were consistent across all five sampling locations (primarily silty sands, SM, with little to no plasticity). Test results show that these soils have low to very low permeability (10^{-4} to 10^{-6} cm/s). The erosion rate, based on the characteristics of the soils in this dam, is extremely rapid (Wan and Fell 2004).

Table 4. Summary of laboratory testing of soil samples collected from Dam D.

Sample Location	Sampling Depth (cm)	Soil Classification[1]	Soil Plasticity[1]		Fines Content[1] (%)	Dry Unit Weight[2] (kN/m^3)	Coefficient of Permeability[2] (cm/s)
			PI	LL			
D - 1	53 – 79	SM	NP[3]	16	13	18.3	10^{-5}
		SM	2	16	13		
D - 2	64 – 89	SP-SM	NP[3]	13	11	16.6	10^{-3}
		SP-SC	6	16	10		
D - 3	41 – 66	SM	2	16	22	18.0	10^{-5}
		SM	2	16	14		
D - 4	36 – 61	SM	3	20	15	16.8	10^{-5}
		SM	3	18	13		
D - 5	30 – 56	SM	1	16	17	18.1	10^{-4}
		SM	4	17	13		

[1]Obtained from testing two specimens from bulk sample.
[2]Obtained from tests performed on tube sample. Note that the Constant-Head method is valid for soils with fines contents lower than 10%.
[3]Non-plastic soil.

Figure 31. Sampling locations in Dam D: a) southwest view from Legion Drive, b) southeast view from the crest, c) northwest view from the crest, and d) southwest view from downstream side slope near the sliding zone (∇: vertical sample, O: horizontal sample).

SUMMARY

In 2015, a total of 51 regulated dams in South Carolina were breached and hundreds of other dams were damaged due to extreme precipitation and catastrophic flooding produced from an unusual set of meteorological conditions. This total represents one of the highest numbers of dam failures due to a single event in U.S. history. To better understand these dam failures, this paper presents findings from the field investigation of three regulated dams that were breached and one unregulated dam that was damaged, but not breached, during the event. The four sites selected for case studies were small dams with ages of at least 25 to more than 100 years old. Even though the dams are small, two of the three dams regulated by the South Carolina Department of Health and Environmental Control were considered to be significant-hazard potential structures.

Based on the findings, it is clear that these dams were not designed for this extreme flood event, but the dams were not properly maintained based on the extent of vegetation and observed conditions of the spillways. At this time, it is unclear how the lack of appropriate care affected the structural integrity of these dams. Further investigation of the role of deep-rooted vegetation on small dams, in particular, is warranted.

According to the pre-failure information available for the dams investigated in this study, the overall dimensions of the dams were different, but all were categorized as small dams with approximately 4 m in height and side slopes ranging from 23° to 33°. Dam A was the largest dam investigated with a length of 290 m and a crest width of 16 m. The dam had a two-lane roadway running along its crest. Dam B was 130 m in length, and had a crest width of 6 m. This dam was located near a major road. Dam C was 191 m in length and had a crest width of 4 m. Dam D was 80 m in length and had a crest width of 4 m. Dam D was located within a subdivision and was compromised, but did not breach, during the flood event. Dams A and B were built in 1932 and 1960. Dam C was built in 1900 and is one of the oldest dams in South Carolina. The exact year of construction of Dam D is unknown, but it is expected to be more than 25 years old.

Post-failure observations suggest that the mechanisms contributing to failure differed among the four dams. Two of the dams (Dams A and B) were overtopped, and surface erosion on the downstream slopes was the main cause of failure. Failure of these dams impacted roadways constructed on top of or adjacent to the dams. One of the dams had dense clusters of mature trees growing on the crest at the breach location. Large and deep root systems of the trees were observed. It is unknown whether the trees contributed to failure, but these findings indicate that the dam was not maintained in accordance with regulations. Dam C was not overtopped, and internal erosion around a buried wall within the dam could have been the cause of failure. Dam D was not breached, but severely damaged on the downstream side slope, resulting in a collapse of the emergency spillway that was initiated by erosion of soil underneath it.

The four case studies also provide a synopsis of soil properties, as well as a description of the geotechnical evaluation of the dam failures that can be useful for further dam breach modeling. Based on field samples collected in and around the locations of failure, these earthen dams are comprised mostly of silty sands and clayey sands with moderately to extremely rapid erosion potential. A definable core made of an impervious material was not observed in all of the dams presented in this study.

ACKNOWLEDGMENTS

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