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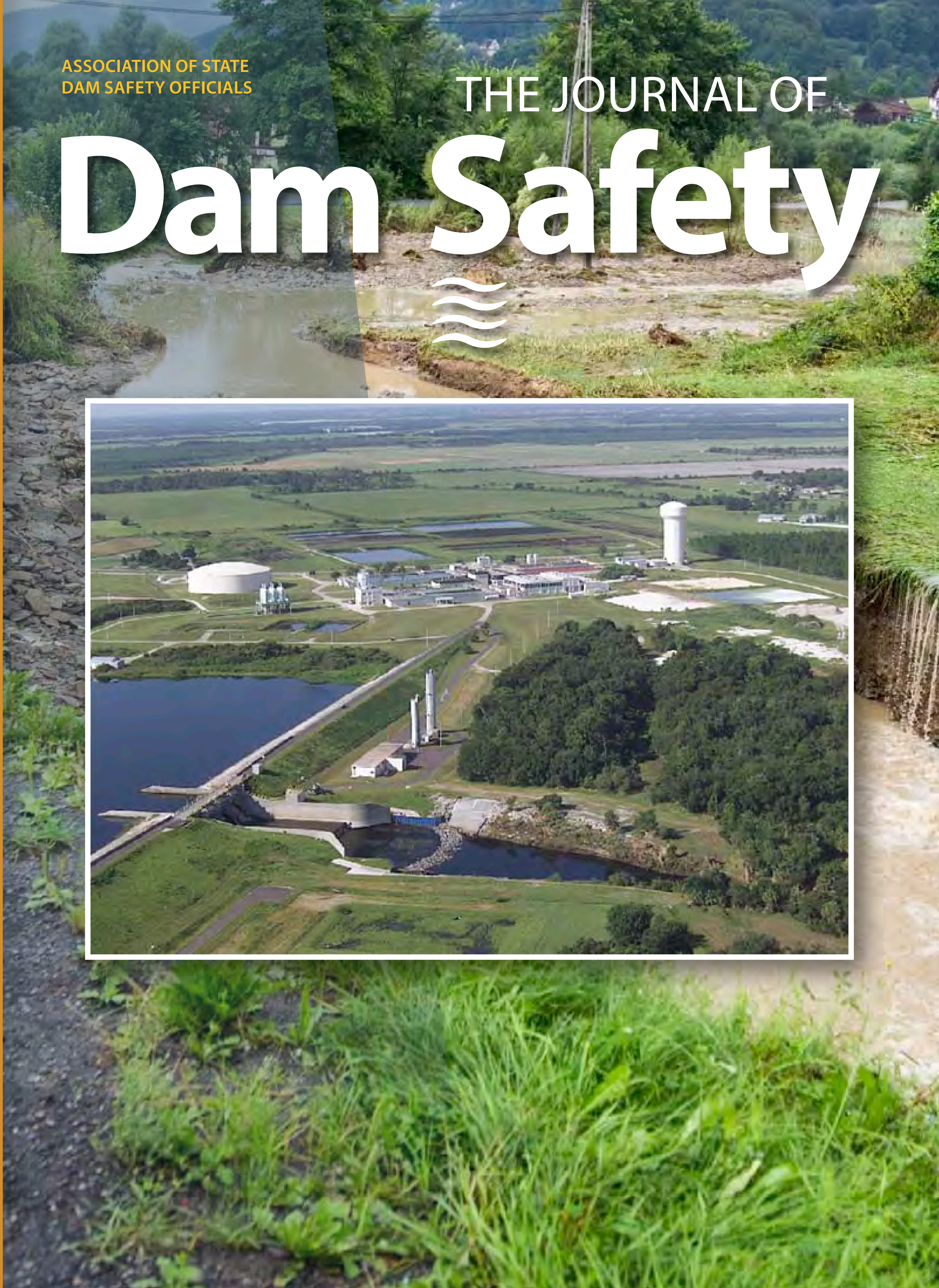

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The Importance of Integrating Historical Data in Preventing a Failure of the

Lake Manatee Dam

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ABSTRACT

An in-depth supplemental inspection in 2013 of the Lake Manatee Dam near Bradenton, Florida identified a serious internal erosion and piping potential failure mechanism. The high risk nature of this dam prompted Manatee County (owner) to initiate a $20M emergency repair, which was completed in 2014. Indications of this potential failure mechanism were manifest in visual and physical observations since the dam went into service in 1967 and were documented during the first official inspection in 1978. This evidence became more apparent in subsequent inspections by seven other engineering groups. In 2013, an engineering group performed an integration of the historical visual and physical observation data and clearly identified the potential failure mechanism. While some of the previous engineering groups had launched supplemental inspections and engineering evaluations to determine the underlying causes for some of their observations, they were unable to clearly identify the potential failure mechanism, and as a result were unable to guide Manatee County to a solution that would stop it.

Given that this internal erosion and piping potential failure mechanism was active and progressing for decades, this case history represents an opportunity to take a closer look at the state-of-practice and how it might be improved to minimize risk through clear identification of active failure modes. Of particular importance is the value of visual and physical historical observation data and how it can be employed in a simple integration technique to lower the overall risks. Unfortunately some owners, engineers and regulators may perceive that these historical observations have a shelf life with their importance decreasing over time. If this is the perception and, if conditions at a dam are deteriorating slowly, the baseline of expected behavior can shift and owners, engineers and regulators can become complacent. It is the purpose of this paper to demonstrate how to avoid this complacency by using a historical data integration technique.

The Lake Manatee Dam is first described. The visual and physical observation data integration technique is then presented. Conclusions are given and recommendations drawn for improvements to the state-of-practice in dam safety engineering.

DESCRIPTION OF DAM

The Lake Manatee Dam was constructed between 1965 and 1967 as an in-stream reservoir on the Manatee River approximately 20 miles upstream of its discharge point into Tampa Bay. Its function is a drinking water supply initially for Manatee County and subsequently for Sarasota County. Land use in the flood zone is agricultural, light-industrial, commercial and residential. The flood zone also includes sensitive ecological resources and state and federally protected species.

A recent aerial view of the dam and its principal spillway is presented in Figure 1. The original dam consisted of an approximately 4,700-foot-long zoned-earth embankment with a clayey core, granular upstream and downstream shells, and a crest elevation of 52 feet (NGVD 29 datum), as shown in Figure 2. After being placed into service, an emergency spillway was constructed in the north abutment.

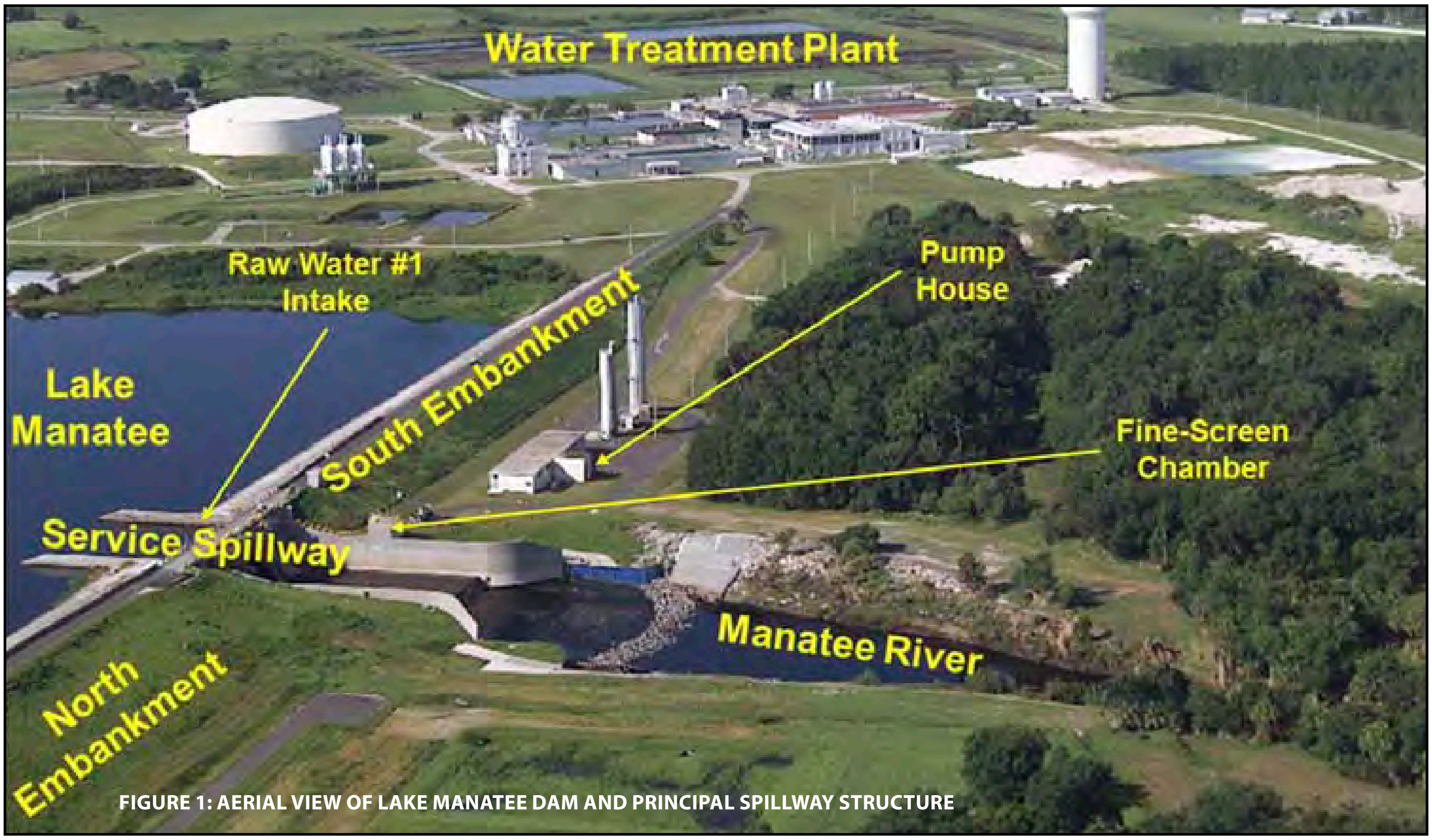

FIGURE 1: AERIAL VIEW OF LAKE MANATEE DAM AND PRINCIPAL SPILLWAY STRUCTURE

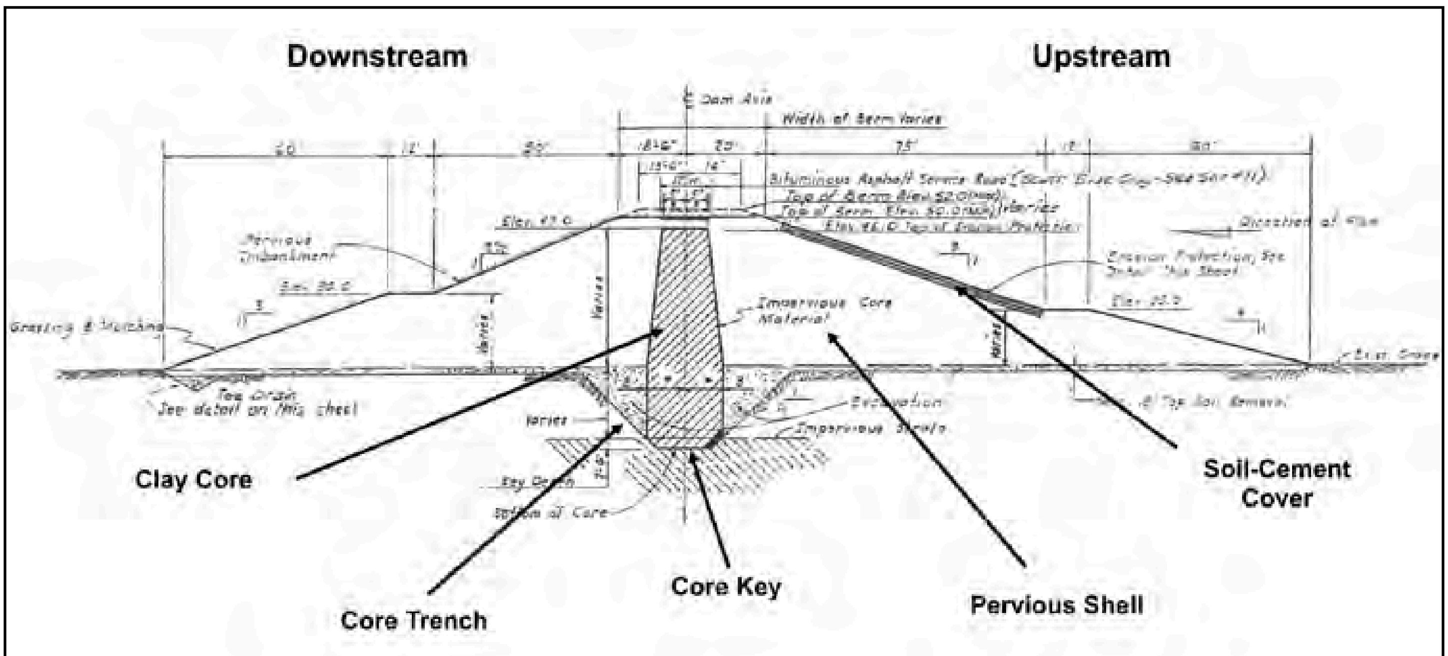

FIGURE 2: ORIGINAL CROSS SECTION FOR LAKE MANATEE DAM

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The present elevation of the crest ranges from approximately El. 51 feet at the service spillway to El. 55 feet in the embankment sections because an additional 3 feet of material was added to increase the embankment freeboard when the emergency spillway was constructed. The original upstream slope was designed at 4H to 1V from the toe to a horizontal bench, above which it was designed with a 3H to 1V slope to the crest and a soil-cement surface erosion protection layer. The upper portion of the downstream slope was originally designed on a 2.5H to 1V slope but was subsequently flattened when the crest was raised and shifted a few feet upstream during the installation of the emergency spillway so that the entire downstream slope is now at a 3H to 1V slope. During this raising, the upper portion of the embankment was slightly over-steepened.

The principal spillway, also called the service spillway, is located approximately 1,500 feet north of the southern abutment and just south of the original Manatee River channel. The service spillway consists of three 15-foot radius tainter gates, each one spanning a 31.5-feet-wide bay. This spillway has upstream concrete approach walls, downstream training walls, and a bare earth approach channel leading to a concrete approach apron immediately upstream of an Ogee-type spillway. It also has downstream concrete training walls and a concrete stilling basin with an end sill. The stilling basin floor slab is ground-founded and consists of individual reinforced concrete sections. The concrete approach walls and the downstream training walls each have an inverted T-shape and together with the Ogee section monoliths are founded on driven H-piles. The dam was designed without a low-level outlet. All water is removed from the reservoir through the two spillways, or by intake pipes to the water treatment plant.

The original clay core of the embankment was keyed into a geologic unit known as the Hawthorn Group with alternating very low and very high permeability layers. Refer to Figure 2. An apparent low permeability layer at the bottom of the core was intended to function as a confining layer. However, just upstream of the embankment and along the south shore of the reservoir, a very deep borrow pit was excavated during construction that apparently extended completely through this confining layer. A toe drain was installed along the entire northern and southern embankments with discharge points in the service spillway downstream of the stilling basin.

The original underseepage cutoff system for the service spillway consisted of a series of driven sheet piles forming a box around the edges of the upstream approach slab and along the front edge of the Ogee spillway sections. Refer to the plan view and cross section for the spillway presented in Figure 3. These sheet piles pass underneath the base slabs of the two approach wall monoliths closest to the

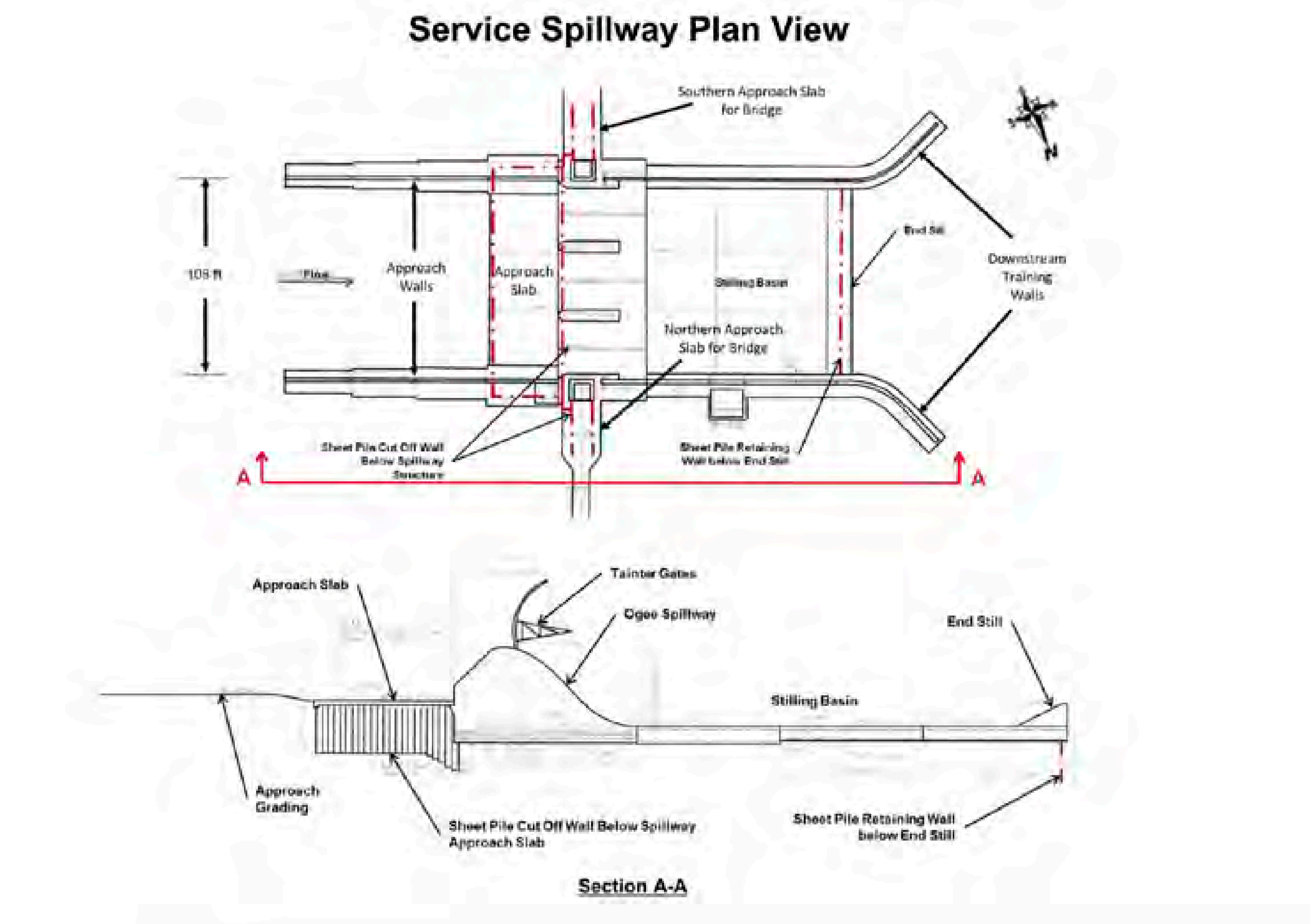

FIGURE 3: SERVICE SPILLWAY PLAN AND CROSS SECTION FROM ORIGINAL DRAWINGS

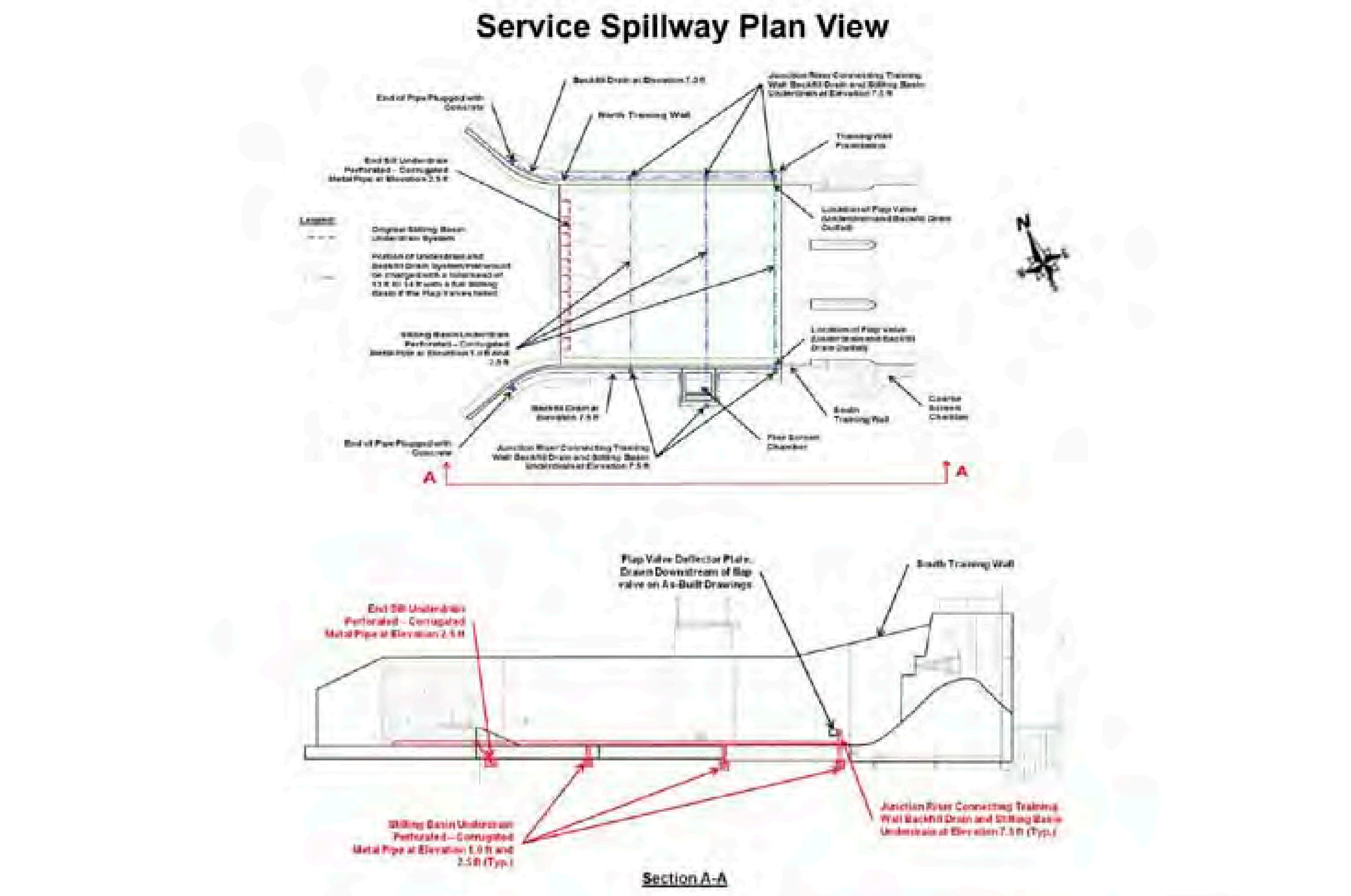

FIGURE 4: SERVICE SPILLWAY PLAN AND CROSS SECTION FOR BACKFILL/UNDERDRAIN SYSTEMS

Ogee section and are connected to another sheet pile cutoff wall that extends from the northern and southern exterior monoliths of the Ogee section underneath the spillway bridge approach slabs and into the embankment's clayey core for a distance of approximately 30 feet. A second set of cutoff sheet piles also extend to the north and south away from the exterior monoliths and parallel to but downstream of the first set of sheet piles. A final sheet pile cutoff wall was placed under the end sill of the stilling basin running north to south between the two base slabs for the downstream training walls. No seepage cutoff was placed under the downstream training walls.

Subsequent to the original design and when a downstream concrete apron was placed over the original bare earth discharge channel beyond the stilling basin to control erosion, additional sheet piles were driven along the edges of this apron, forming retaining walls along its sides and confinement at its downstream edge. However, no sheeting was placed between this apron and the stilling basin and the training wall base slabs.

When voids were discovered under the upstream approach wall base slabs in 2011, additional sheet piling was driven in front of these and inside the spillway channel to provide confinement so that these voids could be filled with tremied grout.

The original under-pressure relief and backfill drain systems for the stilling basin and the downstream training walls are shown on Figure 4 and consisted of two underdrains beneath the stilling basin slab sections and a backfill drain behind the two training walls. The first stilling basin underdrain system consists of two drain pipes running between the training walls that are directly connected by riser pipes through the training wall base slabs to the backfill drain system. The backfill drain system runs along the back side of the training walls just above their base slabs and drains upstream into the stilling basin near the Ogee section through riser pipes and outfalls, one on each side of the stilling basin. A second stilling basin underdrain system runs beneath the end sill and evacuates directly into the downstream channel through a series of 45-degree riser pipes running up through the floor slab and the downstream edge of the end sill.

INTEGRATION OF HISTORICAL DATA

In order to assess the condition of Lake Manatee Dam, dam safety engineers employed a data integration technique using the visual and physical observation record from the annual inspections and the following three steps:

1) Postulate a potential failure mechanism that is consistent with the design of the dam.

2) Mark up an aerial photograph with critical areas on the dam where visual and physical evidence of this potential failure mechanism would be expected.

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Table 1: Location and Types of Observations Consistent with Internal Erosion and Piping

Location Number	Location Description (Refer to Figure 3)	General Types of Observations	Range in Years Observed
1	Northern Approach Wall Below Water	Voids under wall foundations, voids with break in soil-cement slope and underlying embankment washout	2013
2	Northern Approach Wall Above Water	Depressions, surface erosion behind walls, outward movement/ rotation of wall monoliths by as much as 2 inches, large void beneath soil-cement slope paving	1990 - 2013
3	Northern Bridge Approach Slab and Double Row Sheet Pile Cutoff	Weight-of-rod soil blow counts at bottom of clay core, persistent erosion adjacent to bridge, settlement along both sheet pile cutoff walls, subsidence of clay core between sheet piles, voids under secondary approach slab	1978 - 2014
4	Northern Downstream Training Wall Adjacent to Bridge Deck	Persistent erosion, depressions and soft zone in embankment slope, numerous surface irregularities, subsidence and voids under access ladder slab	1985 - 2013
5	Northern Downstream Training Wall Adjacent to Stilling Basin	Irregularities along embankment surface behind wall, outward movement/rotation of wall up to 2 inches, depressions, voids with the suspicion of a "chimney" drain against the wall, 20 cu. yd. sinkhole in 2009, very loose soils in backfill adjacent to the wall from the foundation level and upward	1978 - 2013
6	Western Corner of Northern Downstream Training Wall	Severe erosion, loss of backfill material, large voids under concrete slab behind toe drain outfall box	1981 - 2008
7	Northern Downstream Sheet Pile Wall	Severe erosion, seepage at west edge of sheet pile walls, multiple instances of depressions north of sheet pile wall and loss of backfill material, subsidence behind wall	1986 - 2004
8	Manatee River and Northern and Southern Riverbanks	Erosion, subsidence, large voids under surface protection materials on river banks, seepage daylighting on river banks, formation of large sediment island in river channel	1973 - 2008
9	Southern Approach Wall Below Water	Vortex in lake reported in 1975, large void with break in soil-cement slope and washout of embankment material	1975, 2013
10	Southern Approach Wall Above Water	Outward deflections of wall up to 2 inches, cracks, holes and voids in soil-cement slope with settlement and underlying soft soils	1987 - 2011
11	Southern Bridge Approach Slab and Double Row Sheet Pile Cutoff	Erosion, settlement and depressions along both sides of sheet pile walls and in roadway with a large void under the approach slab and under the secondary approach slab	1981 – 2013
12	Southern Downstream Training Wall Adjacent to Bridge Deck	Loss of soil, erosion and undermining of concrete steps, settlement of stairway and gate motor control slab with a large void under the slab	1978 - 2003
13	Southern Downstream Training Wall Adjacent to Stilling Basin	Voids, depressions and erosion in embankment behind the wall, wall movement towards the stilling basin, large void under concrete pads, soil in close proximity to the wall very loose beginning at the elevation of the bottom of the footing and extending upward, suspicion of "chimney" drain against wall	1978 - 2014
14	Southern Downstream Sheet Pile Wall	Erosion, displacement, and loss of material behind wall, void under concrete pad, flowing water behind wall	1989 - 2013
15	Stilling Basin	Void system underneath stilling basin discovered with dye study and confirmed with coring of floor slab	1997, 2013
16	Downstream Concrete Apron	Settling, cracking, undermining and deterioration of concrete, gap between sheet pile wall and concrete, voids detected underneath concrete	1978 - 2014
17	Downstream Slope and Northern Toe Drain	Artesian pressures in piezometers, sag in toe drain, settlement, depressions, and undulations along ground surface at toe, sedimentation in toe drain, depressions and undulations on downstream slope	1979 - 2013
18	Downstream Slope and Southern Toe Drain	Surficial seepage in toe area, nearly continuous depressions along service road near toe, large depressions downstream of where vortices were observed in the reservoir, settlement of toe drain	1978 - 2008

Table 2: Summary of Inspection Group History

Group Designation	Years of Inspections	General Comments
Group A	1978	Some observations from Manatee County personnel prior to Group A inspection and related during interviews
Group B	1979	Extensive subsurface investigation due to lack of original design information
Group C	1981	
Group D	1983 - 1988	Used subconsultant in 1983 for seepage inspection and evaluation, and first to photograph sediment island during an inspection
Group E	1989 - 1992	First to note movement of approach and training walls
Group F	1993 - 1997	First to specifically identify sediment island in the inspection report and discover voids under stilling basin
Group G	1998 - 2011	Used subconsultant for additional subsurface investigation
Group I	2009	Not a formal inspection but from concerns raised after unsuccessful attempt to dewater the service spillway
Group H	2012 - present	Integrated all previous data and established the presence of active and worsening internal erosion and piping potential failure mechanism

3) Place all visual and physical observation data that may be related to the postulated potential failure mechanism on a series of aerial photographs representing different time intervals and use these to evaluate trends.

Figure 5 presents an aerial photo of the service spillway showing critical seepage paths and locations of significant historical observations as a series of circles, ovals and boxes. These locations are numbered and summarized in Table 1 with the general types and timeframes of observations. The northern and southern edges of the service spillway represent the shortest seepage paths from the lake to the river and are where the largest seepage gradients occur. In these areas along the margins between the spillway and the embankment sections, loss of material should be expected if an internal erosion and piping potential failure mechanism is actively occurring.

Since 1978 (eleven years after being placed into service) dam safety inspections have been performed by engineers from eight different engineering groups. In order to preserve the anonymity of these groups and focus on lessons learned, references made to these groups are done by the designations A, B, C, D, etc.

Loss of embankment material on the surface of a dam and/or adjacent to a spillway structure can be interpreted in multiple ways. It could be due to surface erosion from runoff, movement of retaining walls with settlement of the backfill soils, or internal erosion and subsequent settlement. Thus, in determining which visual observations are to be integrated, those identified by the engineers as either caused by surface erosion, or movement of the walls, or by internal erosion and settlement were included.

The visual observations of loss of material made by the various groups of inspectors at the Lake Manatee Dam have generally been interpreted as due to surface erosion. However, after repeated attempts to control surface water, sinkholes developing in these areas, and no continuing outward displacement of the retaining walls, the evidence pointed to internal erosion.

Visual and physical observations from each dam safety inspection were integrated through a series of figures based upon Figure 5. A summary of the inspection history of these groups of engineers is presented in Table 2. This table includes the group designation, the years spanning their inspections, and general comments. Note that in several of these inspections, photographs are included and/or statements are made about the presence of a sediment island in the downstream river channel. If internal erosion and piping is active, soil particles in the embankment and foundation would likely be moved downstream and deposited. Hence, the presence of a sediment island is a strong indicator of this potential failure mechanism.

Figure 6 presents a series of aerial photographs taken of the service spillway for the dam from 1973 to 2013. Considering the photo for 1973, there is the clear presence of sediment islands attached to both the northern and southern discharge channel banks. The original discharge channel design in this location was a cut earthen channel with a uniform slope. Over the years, these islands appear to expand and move somewhat. After the 2003 aerial photograph was taken, a dredging project was completed to remove the island. However, in the 2013 photograph the island appears to be re-forming.

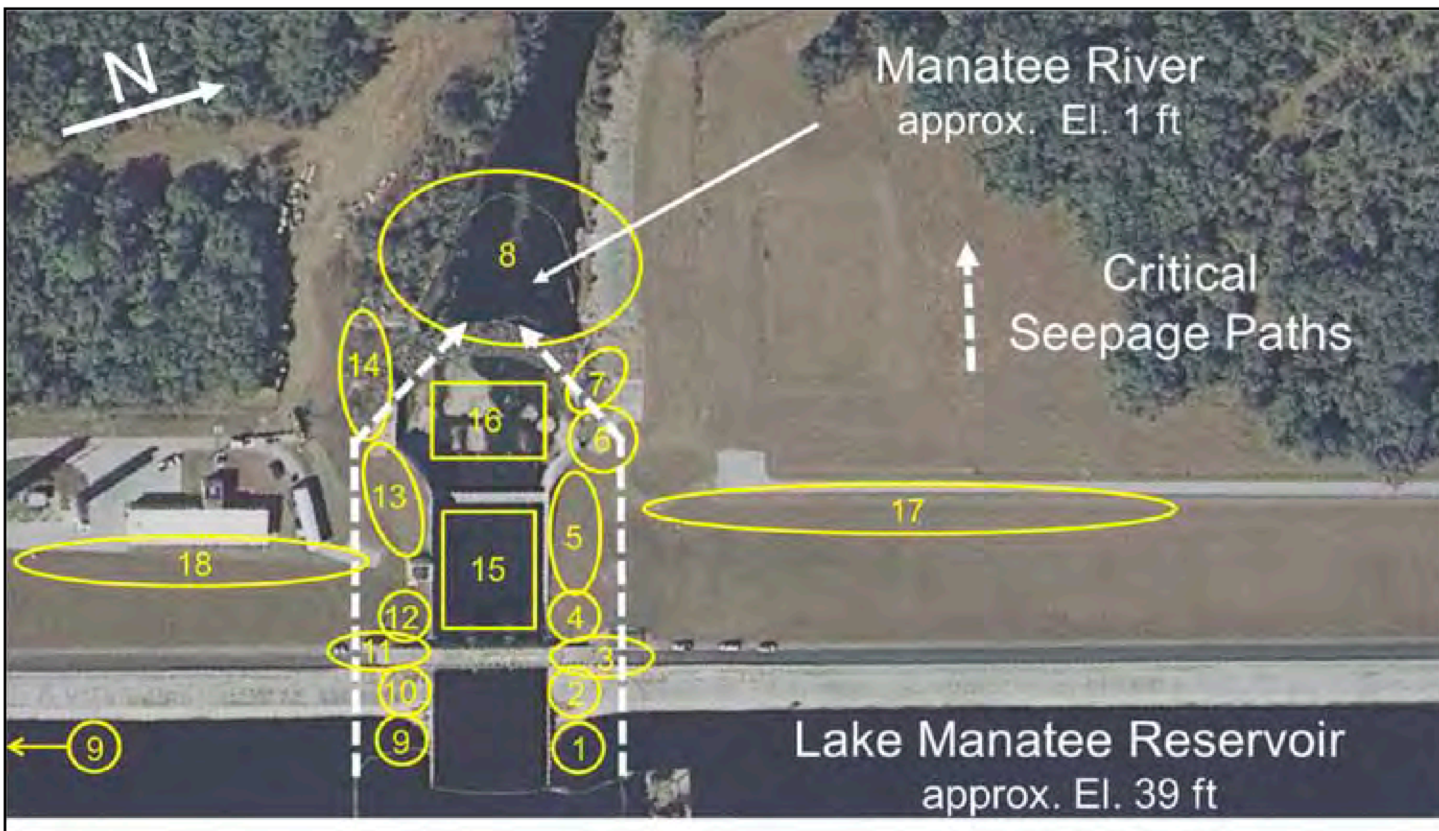

FIGURE 5: CRITICAL SEEPAGE PATHS AND LOCATIONS OF SIGNIFICANT HISTORICAL OBSERVATIONS

FIGURE 6: HISTORICAL AERIAL PHOTOGRAPHS OF SERVICE SPILLWAY SHOWING EROSION AND FORMATION OF SEDIMENT ISLAND

While not definitive, the sediment islands in the aerial photographs shown in Figure 6 are consistent with active material transport and deposition. The build-up of sediments in the discharge channel could be a result of eroded embankment and foundation materials that have been transported to the channel through pipes under the stilling basin, or under the training wall base slabs and downstream apron. However, with such large amounts of material being lost from the banks of the discharge channel as is apparent in these photos, it is possible that some of the sediments forming the islands also came from the channel banks. It is considered likely that both of these mechanisms are present in the 1973, 1978 and 1984 photographs. However, since 1984 when the channel banks had been stabilized, it is considered likely that internal erosion and piping played a larger role in the formation of the sediment island.

The following presents an integration of the visual and physical observations from the historical dam safety inspection reports. Figure 7 presents the locations of the visual and physical observations for each one of the inspection groups.

Group A Phase I Inspection

Group A performed a Phase I Inspection Dam in 1978, eleven years after the commissioning of the dam, and concluded that the embankment compaction during construction was inadequate and that most of the density tests failed to meet compaction requirements. The sheepsfoot compactor had widened steel plates welded onto the feet and the double drum compaction roller was pulled behind a tractor at about 12 mph to 15 mph, far in excess of normal compaction speeds. The soil moisture conditioning process used a lay-down area that was too small, resulting in nonuniform water contents of the fill soils.

Group A concluded that the structure has some major deficiencies which require immediate attention, including inadequate spillway capacity, inadequate seepage control, and inadequate performance of the toe drain.

Specific observations made by Group A are indicated on Figure 7a and include:

a) vortices in the reservoir reported by the operators during low-pool conditions adjacent to the southern approach wall and along the southern embankment;

b) an existing damp area on the downstream slope at approximate Station 12+00 (300 ft south of the service spillway);

c) existing depressions in the service road at approximately Station 8+00 (700 ft south of the service spillway) downstream of where one of the vortices occurred;

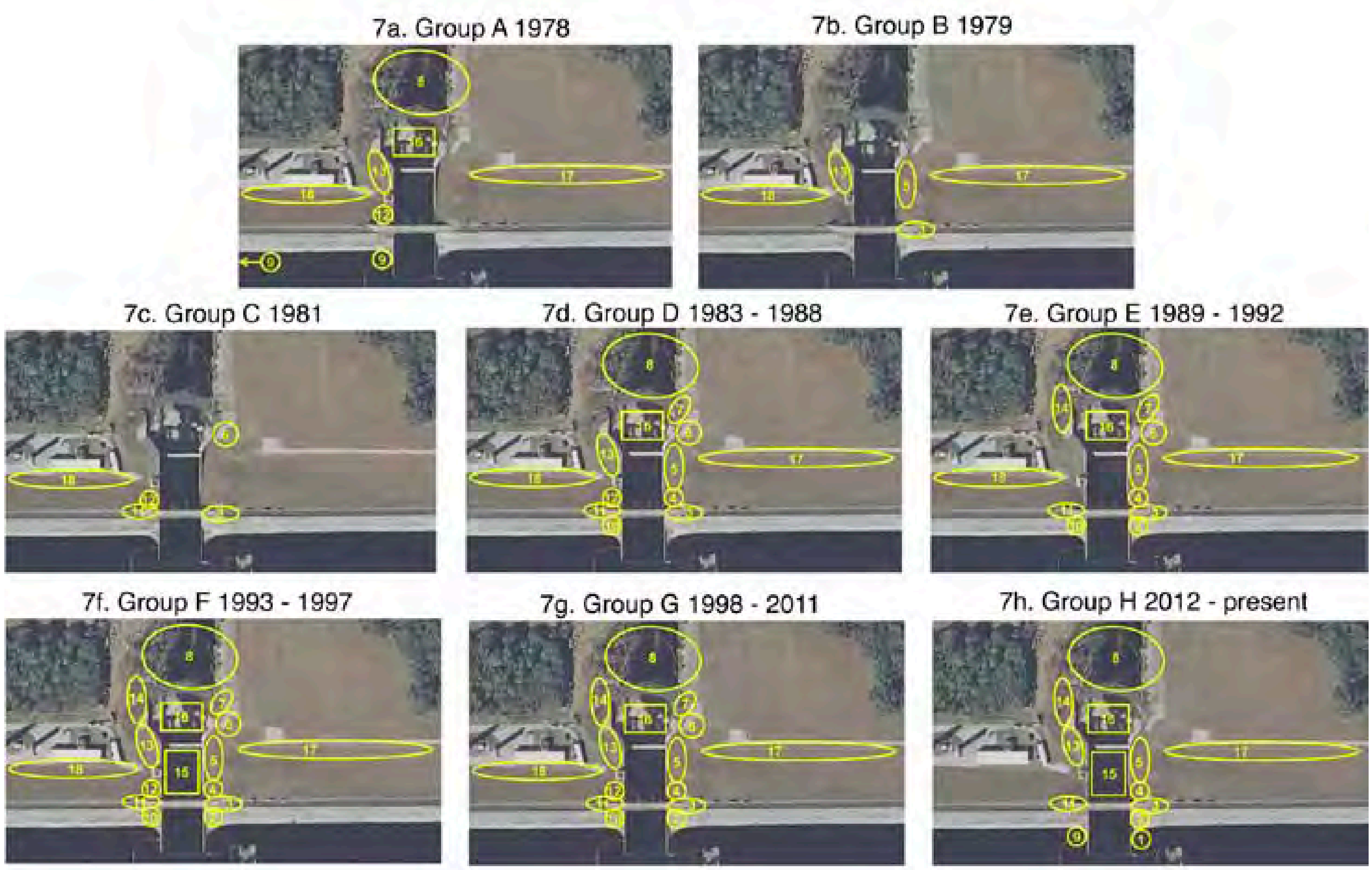

FIGURE 7: LOCATIONS OF CRITICAL VISUAL AND PHYSICAL OBSERVATIONS

d) a 3 ft diameter by 2 ft deep sinkhole immediately adjacent to the south training wall and directly above the existing toe drain outfall;

e) loss of embankment material under the concrete stairway between the bridge deck and the southern downstream training wall;

f) nearly continuous series of depressions in the toe road on the south embankment with wet spots and two conical depressions approximately 6 ft in diameter and 6 inches deep at Station 8+00 (700 ft south of the service spillway);

g) some settling of the southern portion of the embankment (approximately 2 ft relative to the general embankment elevation);

h) nearly continuous series of depressions along the toe of the northern embankment; and

i) extensive erosion downstream of the stilling basin and the subsequent placement of a concrete slab with sheet pile cutoffs (downstream apron) to decrease this erosion after construction.

Although not definitive, these observations are consistent with active internal erosion along the south side of the service spillway on both the upstream and downstream sides of the embankment core and in the toe areas of the embankment.

Group B Phase II Inspection 1979

Group B performed a Phase II Inspection of the Lake Manatee Dam in 1979. Given a lack of available information, an extensive field investigation effort was deemed necessary. The program included twelve test borings, six piezometers, and two pits at each end of the toe drain.

Specific observations by Group B are indicated on Figure 7b and include:

a) loss of drilling fluid circulation and weight-of-hammer blow counts indicating very loose and soft soils at or near the bottom of the core at multiple locations including immediately north of the service spillway;

b) continuing erosion on the embankment slope just north of the service spillway downstream training wall;

c) possible artesian pressure conditions at the embankment toe approximately 100 ft north of the service spillway at Station 17+00;

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d) 2 ft diameter by 3 ft deep depression behind south downstream training wall;

e) practically continuous series of depressions in the toe road on the southern embankment of the dam; and

f) toe drain collecting sediments and not functioning as designed, creating wet spots in the downstream toe areas on the south embankment.

These observations indicate that in 1979 there was not only continuing evidence of active internal erosion on the south side of the spillway and in the downstream embankment toe areas, but there was also evidence that such a process may have been active on the north side of the spillway as well.

Group C Inspection 1980 – 1981

Group C performed an annual inspection and made the following observations indicated on Figure 7c:

a) erosion and loss of embankment material along the upstream side of the sheet pile cutoff walls north and south of the spillway bridge;

b) severe erosion and loss of material on the west end of the northern downstream training wall;

c) erosion and undermining of the concrete stairway next to the southern downstream training wall; and

d) a previously wet area reported to inspectors between the downstream toe and the service road of the south embankment at Station 12+00 approximately 300 ft south of the service spillway.

Taken together, these observations are consistent with active internal erosion transporting embankment/foundation materials along both the northern and southern edges of the service spillway and in the embankment to the north and south of it.

Group D Inspections 1982 – 1988

Group D performed a series of inspections and commissioned a supplemental geotechnical subsurface investigation using another engineering firm. Group D observations are shown on Figure 7d and are as follows:

a) lost the circulation of drilling fluid and very loose/soft soils in the clay core just north of the service spillway;

b) piezometer levels at Station 6+00 (approximately 900 ft south of the service spillway) are above reservoir elevation, indicating groundwater flow from the southern abutment.

c) artesian pressures coming from deeper soil layers in toe area and further downstream at Station 17+50 (approximately 150 ft north of service spillway and in the location of the original river channel) and a zone where piezometric water elevations increased moving downstream of the dam;

d) erosion and loss of material along the sheet pile cutoff walls along both the northern and southern bridge approach slabs of the service spillway;

e) 3/4-inch outward displacement of southern approach wall monolith at the water intake structure for the water treatment plant (the first reported movement of one of the service spillway walls);

f) undulations in the soil-cement surface cover on the upstream side of the dam near the northern and southern approach slabs to the bridge;

g) severe erosion and loss of material immediately adjacent to the north downstream training wall and along the downstream riverbanks, resulting in undermining of the surface protection materials, and a photograph showing the edge of the apparent sediment island in the downstream river channel;

h) erosion and undermining of the embankment materials under the stairway behind the southern downstream training wall;

i) depression behind the south downstream training wall;

j) depressions in old baffle block locations in downstream concrete apron; and

k) settlement of the northern toe drain along with some unknown white substance being carried by the water in the drain.

In 1986 Group D concluded that after several attempts to provide surface protection to remediate the severe surface erosion occurring immediately downstream of the northern training wall (along the riverbank), "…it is probable that the exit of groundwater is a factor".

Persistent high pore water pressures (some of which were artesian) in the downstream toe area just north of the service spillway and an unknown white substance being washed through the northern toe drain, along with very soft materials at the bottom of the embankment core led Group D to hypothesize in 1988 that a change was occurring in the natural clay stratum beneath the dam in the vicinity of the service spillway. They suggested that the increase in pore water pressure could be due to the presence of a porous lens beneath the dam, the dissolving of phosphates within the soils, or a change in the drainage system in the original cutoff layer of the dam. They were so concerned about the apparent changing subsurface conditions of the original seepage cutoff stratum for the dam on the northern side of the service spillway that they stated: "Depressing the toe drain to or very near this stratum could entail substantial risk unless the reservoir level was lowered appreciably and/or the groundwater in the area was controlled."

Taken together, these observations are consistent with active internal erosion and piping causing a loss of embankment and/or foundation material along both the northern and southern edges of the service spillway and in the embankment section to the north and south.

Group E Inspections 1989 – 1992

Group E made the following observations as indicated on Figure 7e:

a) a depression and erosion in the soil-cement slope along the northern approach wall;

b) outward deflections of up to 2 inches on both the northern and southern approach wall monoliths (this is the first reported movement of the northern approach wall in an inspection report);

c) depressions and erosion adjacent to the northern bridge approach slab (both upstream and downstream) for the service spillway bridge;

d) several locations where piezometric water elevations (PWE's) were either higher than the reservoir level or where they experienced fluctuations of a larger magnitude than corresponding fluctuations in the reservoir level;

e) seepage between the northern downstream training wall and sheet piling;

f) holes in the backfill behind the northern downstream training wall and sheet pile extension;

g) depressions along the sheet pile cutoff wall and cracking of the bridge approach roadway adjacent to the south approach wall;

h) separation of sheet pile wall sections and loss of backfill material downstream of south training wall;

i) deterioration of the downstream concrete apron with sheet piling separating from downstream edge;

j) seepage from downstream northern river bank with two slope instabilities adjacent to the sheet pile wall extension and further downstream, and a photograph of a sediment island in the downstream river channel; and

k) depressions and wet zones over the toe drains on both the northern and southern embankments, including a depression in the roadway below the dam at Station 14+25 on the southern embankment.

While Group E concluded that PWE's that are higher than the reservoir elevation are probably due to errors in readings or a plugging of the piezometers, it is also possible that such conditions could be due to other sources of groundwater flow such as from the abutments (as postulated by Group D) or from artesian conditions in underlying aquifers.

In describing the holes discovered behind the northern downstream training wall and sheet pile extension during their 1992 inspection, Group E alluded to the potential for internal erosion, "The holes could have been formed by underground seepage leading to the bottom of the spillway wall."

Outward deflections of training walls in the absence of changes to loading conditions are consistent with a decrease in lateral ground support along the upper portion of the support piles. This decrease in lateral support may be the result of soils surrounding the support piles being either physically removed or loosened by internal erosion processes, and/or may be the result of decreases in the surrounding soil effective stresses caused by upward seepage gradients.

Group E photographed the presence of a sediment island in the downstream river channel in 1992 but did not comment on it specifically in their report.

Group F Inspections 1993 - 1997

Group F identified a potentially serious condition related to the observed movements of the approach and training walls. They also performed a dye study in the stilling basin underdrain and training walls backfill drain systems, as a result of reports from operators stating that running water could be heard through underdrain and backfill drain outflow pipes. The following observations are identified on Figure 7f:

a) erosion, cracks and depressions in the soil-cement covering the slope adjacent to both the northern and southern approach walls;

b) erosion and settlement of embankment materials immediately adjacent to cutoff sheet pile walls on the bridge approaches and adjacent to the downstream training walls;

c) outward displacements or rotations of both northern and southern approach walls and both northern and southern downstream training walls;

d) evidence of vertical seepage from foundation soils into bottom of core at Station 17+00 approximately 100 ft north of the service spillway (although there are irregularities in reported tip elevations of piezometers)

e) voids and depressions behind both the northern and southern downstream training walls with possible drainage "chimneys" into either joints between the retaining wall monoliths or into a void caused by the outward displacements of the walls;

f) large erosion areas behind both downstream training walls near the junction of the sheet pile cutoff walls under the bridge approach slabs;

g) erosion and loss of surface protection material on northern riverbank and a sediment island in the downstream river channel;

h) a void system connecting the southern training wall base slab to the stilling basin end sill and extending underneath the downstream concrete apron;

i) a depressed phreatic surface behind the northern downstream training wall at Station 17+00 approximately 100 ft north of the service spillway indicating seepage from the downstream embankment shell towards the stilling basin; and

j) settlement, depressions, undulations, and bulging of the downstream slope near the locations of the northern and southern toe drains and no direct correlation between toe drain discharge and lake level.

In 1995, Group F placed dye into the outflow pipe on the southern training wall and flushed it with 40 gpm of water to see where the dye would emerge, but to no effect. They then filled the stilling basin with water and observed water freely rushing into the drain. Dye was observed flowing out of the downstream face of the end sill at the end of the stilling basin, through the 4 inch diameter pipes that serve the 8-inch end sill underdrain. This water was being discharged with enough pressure to cause it to project upward about 2 feet, due to the angle of the pipes.

Subsequent to this dye study, representatives of Manatee County repeated the same test but this time plugged the outflow pipes for the end sill underdrain. They found that after a period of time, dye was seen exiting through the discharge points of the concrete apron underdrain system downstream of the stilling basin. As previously noted, this concrete apron and underdrain system were added subsequent to the original construction when severe erosion had damaged the bare earth discharge channel.

Based upon the results of these dye studies, and the demonstrated interconnection of the various underdrain systems, Group F concluded that groundwater was apparently draining through an eroded path(s) below the stilling basin slab. In order for the eroded path(s) identified by Group F to connect with voids under the concrete apron with a high-capacity flow path, these void(s) would most likely extend under the training wall base slabs around the edges of the cutoff wall.

Group F reported the formation of a sediment island in the downstream river channel closer to the southern bank in their 1993 inspection report. However, they did not comment on the source of the sediment.

Group F observed that piezometers in the embankment toe area near the southern abutment did not respond directly to lake levels. They also observed that the toe drain discharge measurements did not correlate directly to lake levels and postulated initially that the recording units were not functioning correctly. They noted in later inspections that the high flow rates in the toe drain appeared to correlate with high piezometric water elevations. These results indicate that groundwater seepage may be coming from the abutments and/or from underlying formations under artesian conditions.

Group F noted that there were spikes in the water pressures recorded under the Ogee section of the spillway by as much as 7 to 8 ft. This observation is consistent with the formation of a void system under the training wall foundations that extends close to the Ogee section acting like a secondary underdrain system.

Group F concluded that the observed movement of all four retaining walls in the service spillway was caused by changing loading conditions on the walls due to saturation of the backfill.

Group F concluded in 1995 that, "The apparent erosion under the stilling basin slab is potentially a serious problem. The extent of the erosion is unknown at this time. The undermining of the structure, if extensive enough, could cause damage to the stilling basin and/or training wall footings. It is also possible that the erosion could progress from the downstream side of the dam to the upstream side. Such erosion could, therefore, threaten the integrity of the dam and perhaps could result in a breach in the dam." There was no mention of the potential for voids under the downstream training wall base slabs.

Group G Inspections 1998 - 2011

Group G subcontracted with another engineering firm to perform geotechnical subsurface investigations focusing on the embankments behind the northern and southern downstream training walls. The Group G inspection reports contain the following observations that are also indicated on Figure 7g:

a) large voids, settlement, and cracking on the upstream slopes behind both the northern and southern approach walls and voids under approach wall base slabs;

b) subsidence of the clay core below the northern bridge deck approach slab, soft soils in the clay core, and settlement of the embankment along the sheet pile cutoff wall/embankment interface at the southern approach slab;

c) settlement, erosion ruts, and depressions under concrete slabs behind both the northern and southern downstream training walls adjacent to the sheet pile cutoff walls;

d) large voids, erosion ruts and loose to very loose soils in the embankments behind the northern and southern downstream training walls, including the formation of a 20-cubic-yard sinkhole behind the northern training wall in 2009 following a heavy rainfall event resulting in a release with high tailwater;

e) large voids, settlement, erosion and undermining of concrete mats and surfaces and loss of backfill material immediately downstream of the training walls, behind the sheet pile walls and along both the northern and southern riverbanks, accompanied with movement of the sheet piles;

f) continued presence of a sediment island in the river channel downstream of the concrete apron until 2003 when it was removed by dredging; and

g) settlement of and sedimentation in the northern and southern toe drains.

The creation of a 20-cubic-yard sinkhole behind the northern downstream training wall indicates that the void system previously identified by Group F under the stilling basin probably extended under the northern training wall base slab and grew large enough to consume 20 cubic yards of embankment material.

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Group H Inspections 2012 – 2014

Group H supplemented their inspections with diver inspections, ground penetrating radar, SPT borings, coring through the stilling basin floor slab, and video taping of the northern and southern toe drains. The following general observations were reported and are indicated on Figure 7h:

1) large voids and collapse of the soil-cement slope paving below the water surface adjacent to the northern and southern approach walls;
2) large void under the soil-cement paving above the lake level and adjacent to the north approach wall;
3) large voids under the primary and secondary bridge deck approach slabs and between the sheet pile cutoff walls on both the north and south sides of the service spillway;
4) erosion, subsidence and loose to very loose embankment fill soils behind the north and south downstream training walls;
5) undermining of slope erosion protection on the north riverbank;
6) flowing water between the sheet pile wall and southern training wall;
7) multiple voids under the stilling basin floor slab that extend under the training wall base slabs;
8) multiple voids under the downstream concrete apron; and
9) depressions in the downstream toe area of northern embankment just north of the service spillway.

Prior to the data integration technique described herein, dam safety engineers from Group H concluded in 2013 that "The Lake Manatee Reservoir Dam is well maintained and is in very good overall condition." However, voids under the stilling basing that extend underneath the base slabs of the training walls and out to the river under the concrete apron represent a series of pipes supported by reinforced concrete roofs that have probably worked their way back to or very near the core of the dam. Given that other inspectors found evidence of voids under the approach wall base slabs, it is likely that very high gradients exist between these upstream voids and the voids under the training walls. These gradients are likely acting on the core of the dam and the materials beneath the core immediately adjacent to the spillway and are most likely responsible for the observed loosening and settlement of the core materials beneath the two approach slabs to the spillway bridge.

Group I Letter

In 2009, Group I developed a set of design plans for the installation of a cofferdam in support of additional work on the tainter gates and approach channel. After an unsuccessful attempt to construct and dewater the cofferdam in 2011, they issued an unsolicited letter to Manatee County expressing significant concerns about the condition of the dam based upon observations made during the course of their work. They said that their observations "…could be an indication of on-going internal degradation of the Dam's shell containment and clay core, the extent of which may not be fully measureable or even detectable without additional investigation."

The following is a list of conclusions about the condition of the dam from their letter:

a) There are voids beneath the pile supported upstream approach wall base slab.

b) The dam's shell containment material upstream of and immediately adjacent to the clayey core material north of the north approach wall has been significantly loosened.

c) The soil-cement slope protection near the bottom of the upstream slope on the north side of the north approach wall has sloughed and failed.

d) There are potential voids/gaps beneath the downstream training wall base slabs.

e) There is concern about the condition of the corrugated and perforated piping that forms the underdrain system beneath the stilling basin floor slab.

f) There are voids and flowing water conditions beneath the concrete apron beyond the stilling basin end sill.

g) Significant loss of material has occurred in the backfill zone behind the training walls at various times over the life of the structure and has been repeatedly backfilled by Manatee County.

Group I ends their letter by expressing significant concern about the overall condition and integrity of the dam's clay core in the vicinity of the spillway structure. If the loss of material under the upstream approach walls and downstream training walls extends close enough to the clay core and/or seepage cutoff walls, they state that the potential exists for a "significant seepage piping condition to be developed around or beneath the spillway structure. If such a condition is or has developed, it could become cause for the dam to fail by internal erosion in a rapid manner."

FINDINGS AND RECOMMENDATIONS FROM 2013 SUPPLEMENTAL INSPECTION

In late 2013, dam safety engineers from Group H found that there was an active and progressing internal erosion and piping potential failure mechanism in the dam and foundation that could have resulted in an uncontrolled release of the reservoir. In early 2014, these engineers met with representatives of Manatee County to review their findings and presented the following conclusions:

1) Lake Manatee Dam is in a severely distressed state.

2) Without immediate intervention there is a high risk of an uncontrolled release of the reservoir, most likely following a large rainfall event and prolonged opening of the service spillway.

During this meeting, the dam safety engineers also made the following short-term and long-term recommendations:

1) Short-Term (prior to start of hurricane season)

    a. Consider lowering the reservoir.

    b. Reestablish the seepage control function of the dam core (jet grouting, pressure injection, sheetpiling, or similar).

    c. Work with specialty contractors to collect necessary information and develop cost estimates.

2) Long-Term

    a. Fill voids under stilling basin and training walls (jet grouting, pressure injection, excavation and replacement, or similar).

    b. Densify backfill soils behind the approach and training walls (compaction grouting, pressure injection, excavation and replacement, or similar).

    c. Reestablish seepage control for spillway structure and embankment.

The short-term recommendations were implemented during a 2014 Phase I emergency repair involving the installation of a deep (95 feet to 105 feet) seepage cutoff wall under the service spillway and through the northern and southern embankments. The long-term recommendations are to be implemented during a Phase II repair project.

DISCUSSION

When presented together using the data integration process just demonstrated, these visual and physical observations provide a very strong indication that a serious internal erosion and piping potential failure mechanism was active at the Lake Manatee Dam prior to the 2014 emergency deep seepage cutoff wall installation.

The historical visual and physical observation data suggest that shortly after construction a pipe developed underneath both downstream training walls at their western edge, which progressed back upstream towards the reservoir. The contributing factors to the initiation of the internal erosion and piping probably included:

1) a hydraulically connected backfill drain and stilling basin underdrain system with inadequate backflow prevention that aided in the saturation of the embankment;

2) a toe drain system with no backflow prevention that also aided in the saturation of the embankment;

3) an unlined discharge channel immediately downstream of the end sill of the stilling basin;

4) no seepage cutoff under the downstream training walls;

5) a deep borrow pit excavated upstream of the dam near the south shore of the lake and within 1,500 feet of the service spillway that cut through the designed confining layer for the embankment;

6) regional artesian pressure conditions in the aquifer immediately below the confining layer; and,

7) poor soil compaction processes during construction.

The pipe(s) under the training walls and stilling basin of the Lake Manatee Dam probably initiated at the toes of the downstream training wall base slabs beyond the end sill in the area where the discharge channel was originally bare earth. Figure 8 illustrates how the pipe(s) could have initiated with a plan view, section, an idealized cross section (A-A) drawn through the western end of the southern training wall. The same design detail is present on the western end of the northern training wall.

According to the original design drawings, the downstream discharge channel had a bare earth surface starting at El. 7 feet (also corresponding to the top of the training wall base slabs) and then graded down to El. -1 foot where it met the original river channel. During a high tailwater release of water through the spillway, the backfill soils in the immediate vicinity of the training wall are expected to have become saturated during a prolonged release.

The bottom of the training wall base slab has as much as 10 feet of compacted fill placed during construction over the native soils just beyond the heel of these training walls. Under these increased loads, the native clayey soils may have consolidated, forming a gap along the bottom of the pile-supported base slabs at their heel.

Following a high tailwater event, a rapid drawdown condition would have been present behind the training walls due to embankment soil saturation. Due to scouring on the bare earth channel bottom, the soils at the toe of the training would have at least partially eroded. The previously described gap along the bottom of the base slabs at the heel would have experienced the full tailwater elevation head. A rapid drawdown condition with a gap under the base slab would have created a vertical gradient well in excess of 1 in the soils in the river channel immediately in front of the training wall base slabs. With such a large vertical gradient, the soils in front of the retaining walls would have liquefied and a significant amount of material would have been lost from underneath the base slab. This would have occurred even if there was no previous loss of soils due to scour in the discharge channel.

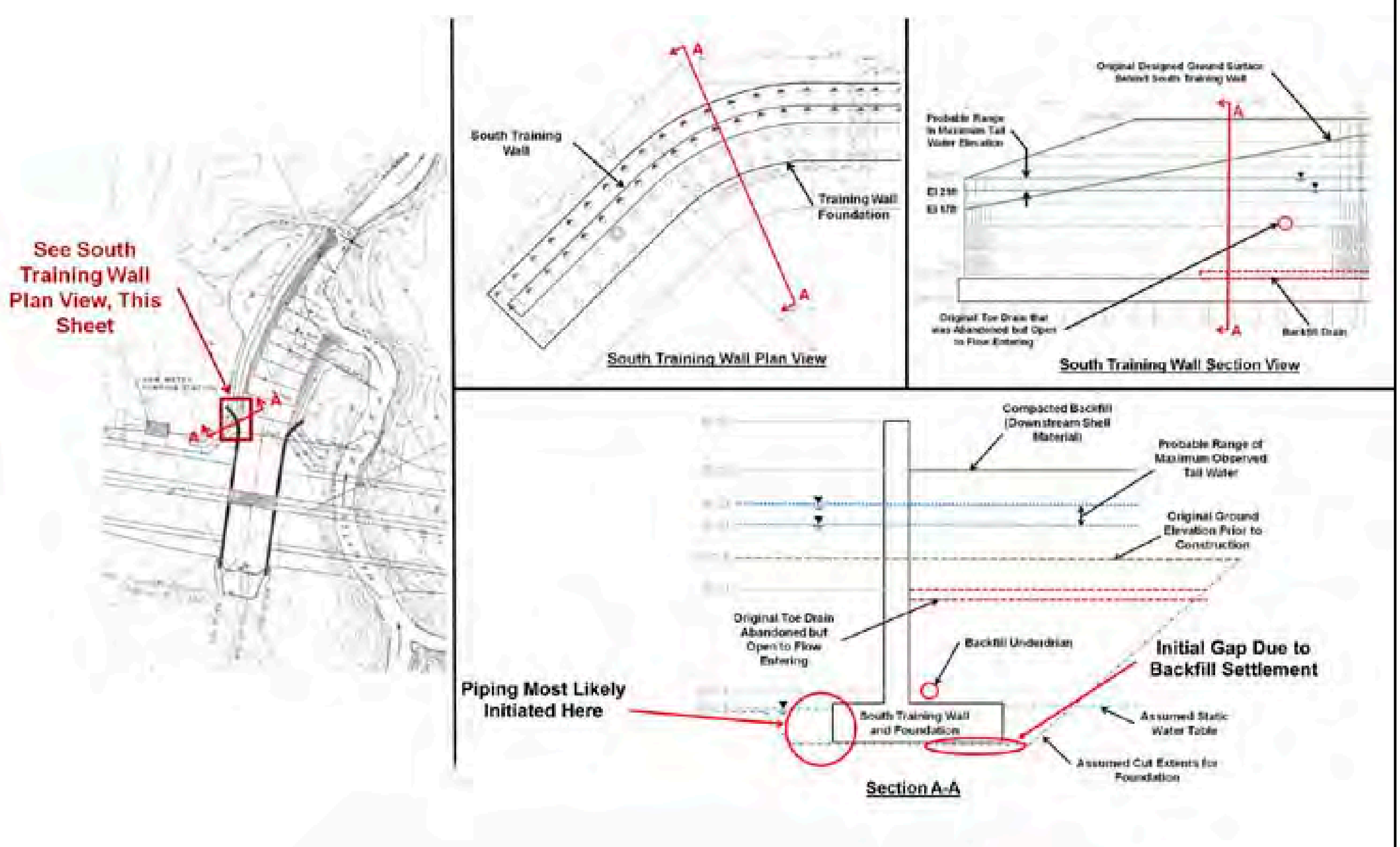

FIGURE 8: PROBABLE LOCATION OF PIPING INITIATING EVENT

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With this initial pipe now formed and under the action of lateral gradients from the reservoir and vertical gradients from the underlying artesian aquifer, soils probably eroded internally from both the embankment and the underlying confining layer. Materials were transported into this pipe network and eventually carried out into the downstream river channel forming a sediment island.

When the concrete apron was placed over the discharge channel floor after construction, but before the first inspection in 1978, it probably slowed down the piping process. However, the pipes eventually extended under the apron, progressed backward under the stilling basin floor slab, and at this point have likely worked their way upstream to the two seepage cutoff walls on either side of the service spillway bridge deck. With much shorter seepage paths resulting in higher gradients, embankment and foundation materials in the vicinity of these two sheet pile cutoffs and near the approach walls have been eroded and transported downstream into the river channel.

CONCLUSIONS

The Lake Manatee Dam was in a severely distressed state and could have experienced a breach following a high tailwater release due to the presence of an active internal erosion and piping potential failure mechanism most likely initiated immediately after construction and becoming more severe over time. This internal erosion and piping potential failure mechanism was caused by one or more of the following factors.

1) Design flaws that:
   a. enhanced backfill/embankment erosion during spillway releases;
   b. provided for an unfiltered exit of embankment and foundation soils at the downstream edge of the training walls; and
   c. created a roof for a pipe extending under the base slabs of the approach walls, the downstream training walls, and the stilling basin (separated only by a narrow section of embankment core and two sheet pile walls).
2) Construction flaws that:
   a. resulted in very loose and highly variable compacted fill in the embankment; and
   b. cut through the confining layer for the clay core of the embankment in the deep borrow pit in close proximity to the embankment dam and spillway.
3) Regional artesian pressures in the aquifer immediately beneath the confining layer for the clay core that created vertical seepage gradients at the bottom of the embankment and service spillway that may not have been accounted for in the design.

IMPROVEMENTS TO THE STATE-OF-PRACTICE

The internal erosion and piping potential failure mechanism that developed throughout the life of Lake Manatee Dam suggests several recommendations that may be useful for improving the state-of-practice in dam safety engineering.

Incorporate Data Integration Techniques

Human nature leads us to more easily differentiate changes in behavior rather than to integrate observations over time. Differentiation is very important for dam safety engineering, especially if behavior is deteriorating rapidly. However, if the behavior is developing slowly and our focus during inspections is on changes in behavior, underlying potential failure mechanisms can remain undiagnosed. Data integration for Lake Manatee Dam was time consuming and tedious but was essential to clearly identifying the active potential failure mechanisms. Twenty-two separate dam inspection reports were reviewed along with all available design documents. The inspection reports totaled over 5,000 pages and these were reviewed multiple times in order to extract all of the relevant information.

Avoid Following Interpretations of Prior Inspectors

All data, observations, engineering calculations, opinions and recommendations carry uncertainty. Given that it is very difficult to be 100% certain about the interpretation of any one piece of information and given that there are often multiple viable interpretations, dam safety engineers may assign an interpretation that causes the least disruption to the status quo, especially if prior engineers have made similar interpretations. These same interpretations might then be carried forward without independent critical evaluation.

For example, when the engineers from Group A observed a sediment island in the discharge channel based upon contemporary aerial photographs and the available as-built drawings, they also found evidence of vortices in the reservoir, depressions and wet areas in the downstream toe and along the back of the downstream training walls, and extensive erosion along the banks of the downstream river channel. However, they did not interpret the sediment island as being indicative of internal erosion and piping or else they would have recommended actions to address it. Subsequent groups of engineers found additional evidence of this potential failure mechanism but apparently discounted the presence of the sediment island because it had been there in prior inspections.

The original interpretations were thus carried from inspection to inspection until some of the latter groups started realizing that something may be wrong and a senior dam safety engineer in the final group looked at the dam from a different perspective and performed an integration of the historical data and concluded the potential failure mechanism was severe, active and progressing.

Formalize Dam Safety Engineering Training in Forensic Engineering

Our current state-of-practice in dam safety engineering may be limited by a lack of formal training in forensic engineering. Although engineering design and forensic engineering use the same basic science and engineering principles, they are fundamentally different. Engineering design starts with assumptions about the environment and how our facility will interact with it, and is guided by well-established design codes and procedures that help us to arrive at a cost effective and low-risk solution. Forensic engineering starts from a collection of disparate observations, which may or may not be sufficient, and seeks a scientific/engineering explanation for these observations. Dam safety engineers are thus required to be detectives, which most dam safety engineers learn by on-the-job training.

Forensic training for dam safety engineers should therefore not only include investigative techniques to arrive at valid conclusions, but should also include reviews of basic scientific and engineering principles necessary to interpret observed behavior.

Standardize Inspection Protocols

All dams should have standardized inspection protocols, such as US Army Corps of Engineers ER 1110-2-156. Such protocols help owners plan appropriate levels of effort for inspections and insure consistency and thoroughness between different dam safety engineering groups. Such protocols should include daily observations by dam operators and maintenance personnel, annual inspections by engineers, and periodic in-depth inspections that incorporate the visual and physical observation data integration techniques described in this article.

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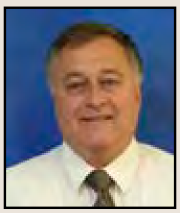

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