High-Risk Flood Control Dams on Difficult Soil Foundations

Gary S. Chow
U.S. Army Corps of Engineers, Galveston, TX

Lori K. Thomas
U.S. Army Corps of Engineers, Galveston, TX

Willis Walker
U.S. Army Corps of Engineers, Galveston, TX

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Gary S. Chow, P.E.
U.S. Army Corps of Engineers
Galveston, Texas, U.S.A.

Lori K. Thomas, P.E.
U.S. Army Corps of Engineers
Galveston, Texas, U.S.A.

Willis Walker, Ph.D. P.E.
U.S. Army Corps of Engineers (Retired)
Galveston, Texas, U.S.A.

ABSTRACT

Addicks and Barker Dams are two flood risk management structures owned and operated by the U.S. Army Corps of Engineers (USACE) and recently classified as extremely high risk. These dams were built in the 1940's in west Houston, Texas, upstream of a densely populated metropolitan area. The dams consist of 11 and 13 miles of rolled earth embankments, outlet structures with five barrel conduits, and uncontrolled spillways at both ends of both dams. The original design of both dams provided for four of the five outlet conduit barrels to be ungated, permitting a combined uncontrolled discharge from both dams of 15,700 cubic feet per second into Buffalo Bayou. Due to urban development throughout the 1940s and 50s, all conduit barrels of both dams were gated by 1963 to allow restricted discharge flows into Buffalo Bayou during normal operating conditions.

These fundamental changes in operations together with the existence of erodible fine sand and silt foundation soil conditions led to the initiation of several potential failure modes at the outlet structures. These have been recently confirmed by the findings of voids beneath the conduits in both dams. Interim measures have temporarily stopped progression of the failures. This paper's presentation mainly focuses on the history and issue evaluations of the outlet structures of these dams and the interim measures and long term solutions under consideration for reducing risks associated with these critical infrastructures.

INTRODUCTION

Addicks and Barker Dams are located in southeast Texas in the San Jacinto River basin approximately 17 miles west of downtown Houston. The reservoirs are strategically located above the confluence of Buffalo Bayou and South Mayde Creek. Beyond this confluence, Buffalo Bayou continues east through downtown Houston, where it joins with White Oak Bayou, and eventually becomes the Houston Ship Channel, which flows into San Jacinto Bay. The majority of both Addicks and Barker Reservoirs fall within Harris County; however, a small portion of Barker Reservoir crosses into Fort Bend County. Addicks Reservoir is situated on the north side of Interstate Highway 10 (I-10) with State Highway 6 (SH 6) bisecting the reservoir north to south. Barker Reservoir is situated on the south side of I-10, west of SH 6.

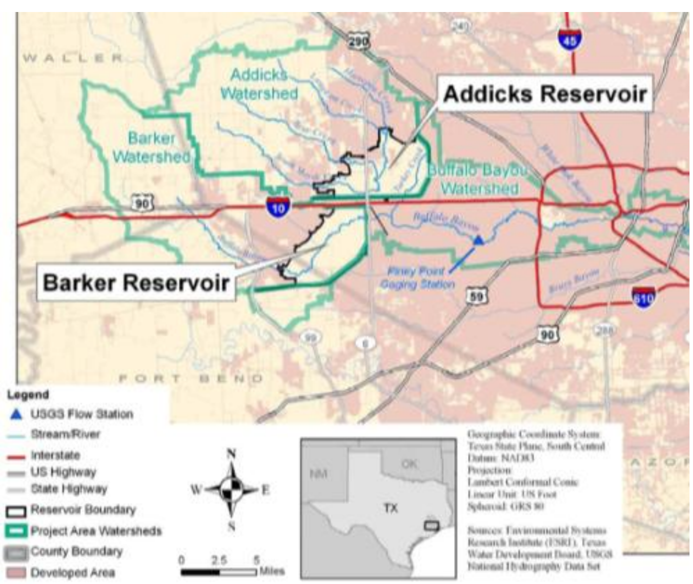
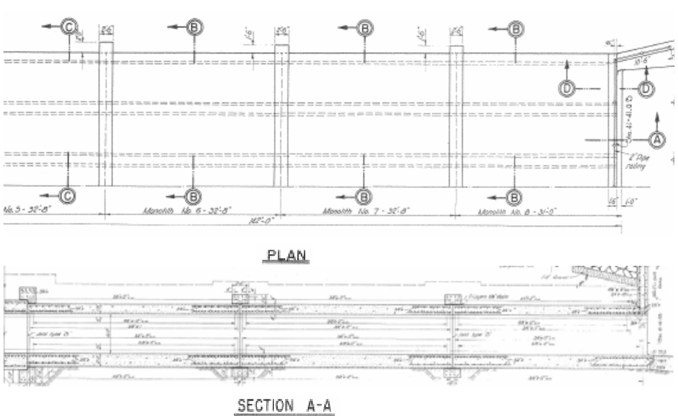


Figure 1 - Addicks and Barker Reservoirs, Project Location

The Addicks and Barker Dams are part of the Buffalo Bayou and Tributaries flood risk management system located on the west side of Houston, Texas. This system provides flood risk management benefits for the City of Houston, the fourth largest city in the United States. Over 4 million people live and work in and transit through the Buffalo Bayou watershed. Industrial, commercial, and residential development is located throughout the Buffalo Bayou corridor. In addition to buildings, this development includes highways, roads and utilities, and water and sewerage treatment facilities. These dams serve as detention basins designed to collect excessive amounts of rainfall during storm events. Following a storm event, the reservoirs release the collected rainfall down Buffalo Bayou at a controlled rate that prevents flooding in downtown Houston and the urban areas west of downtown.

Both dams were authorized by the U.S. Congress as flood control system and both were constructed using similar construction techniques during the same time frame (Barker Dam constructed between 1942 and 1945, and Addicks Dam between 1946 and 1948). The dams are also located very close to each other. While there are many similarities between the two dams, there are also some unique, features as described below:

The Addicks Dam project features include an earthen dam, concrete outlet works, and uncontrolled spillway. The earthen dam consists of an unzoned, random fill embankment that is 61,166 feet long and 48.5 feet above the original streambed. The top of the dam elevation currently ranges from 117.4 to121 feet and the crest is 12 feet wide. The outlet works (shown in Figure 2) have five 8 feet by 6 feet concrete conduit barrels controlled by six gates. Both ends of the dam are armored with roller-compacted concrete and serve as uncontrolled spillways. Existing ground at the north end of the Addicks Dam is at elevation 108 feet and ties into the spillway crest at 112.5 feet. The existing ground at the south end is at elevation 111.0 feet and ties into the spillway crest at elevation 115.5 feet.



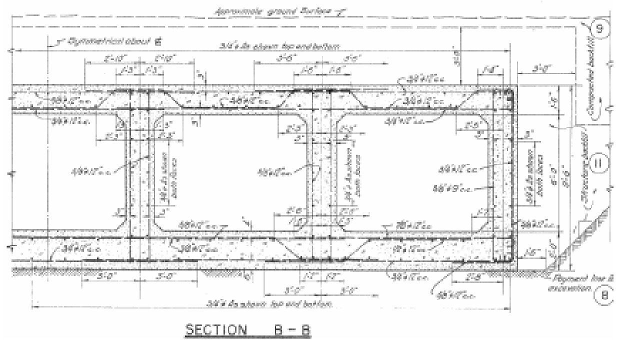


Figure 2 - Addicks Dam Conduits Layout

Barker Dam project features also includes an earthen dam, concrete outlet works, and an uncontrolled spillway. The earthen dam consists of an unzoned, random fill embankment that is 71,900 feet long with a maximum height of 42.9 feet at the outlet works. The top of dam elevation currently ranges from 113.8 to 114.7 feet. The outlet works (shown in Figure 3) consist of five gated concrete conduits (9 feet by 7 feet). Both ends of the dam are armored with roller-compacted concrete and serve as uncontrolled spillways. Existing ground at both ends of Barker Dam is at elevation 104.0 feet. The spillway crest at the north end is at elevation 105.5 feet and the south end is at 106.7 feet.

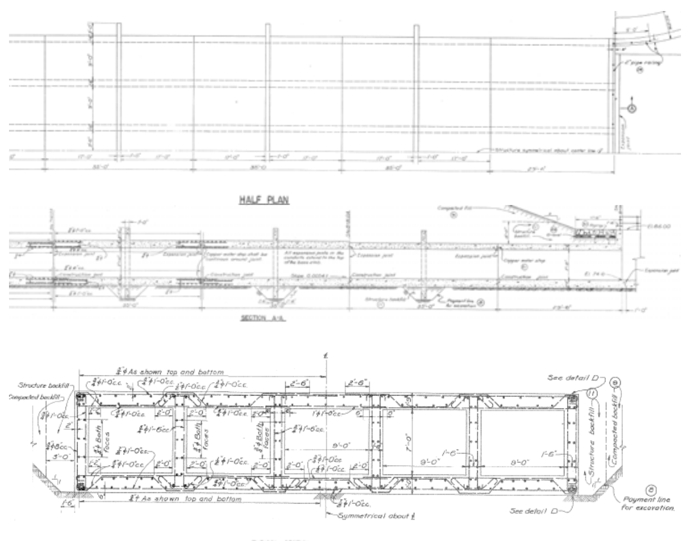


Figure 3- Barker Dam Conduits Layout

The original design for both dams provided for four of the five outlet conduits to be uncontrolled, permitting a combined uncontrolled discharge of about 15,700 cubic feet per second (cfs) into Buffalo Bayou. When two of the four ungated conduits were gated at each dam in 1948, the combined uncontrolled discharge was limited to about 7,900 cfs, which was considered to be the capacity of Buffalo Bayou at that time. Increasing urban development adjacent to Buffalo Bayou during the 1940s and 1950s led to additional potential flood threat by the uncontrolled release from the dams.

Studies undertaken in the 1960 showed the necessity of gating the remaining uncontrolled conduits to allow full control of releases from the reservoirs. At this time, flows during normal operations were restricted to a maximum combined flow from both dams of 2000 cfs at Piney Point – an USGS gauging station that is approximately 9 miles downstream of the dams. The net effect of gating the conduits is higher pool elevations for longer periods of time causing increase duration and intensity of hydraulic loading on the pervious foundation beneath the concrete outlet structures.

Figure 4 - Conduits Showing Ungated Upstream Inlets Following Original Construction Completion

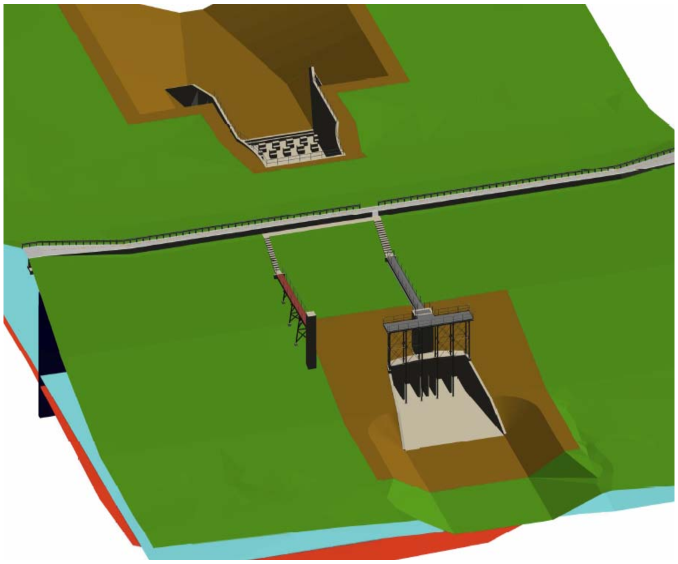


Figure 5a - Configuration of Outlet Works with Currently Gated Conduit Structures

Figure 5b - Conduits Upstream Inlets Showing Currently Gated Structures

GEOLOGIC SETTINGS

The geologic formations in the area of Addicks Dam and Barker Dam are of the Quaternary System and are, successively, the Reynosa Sands, the Lissie Sands, the Beaumont Clay, and recent deposits. These formations dip southeasterly in the same direction as the dip of the land surface but at a much steeper slope; therefore the older formations are found on the headwaters of the streams. The Reynosa Sands appear, if at all, only in the upper reaches of the watershed. The Lissie Formation, which lies unconformably on the Reynosa Sands, is composed principally of thick beds of fine sand containing lentils of calcareous nodules and concretions and is interbedded with clay and silt. The Beaumont formation occupies the flat and featureless coastal plain in a band about 40 miles wide lying between the outcrop of the Lissie formation and the Gulf of Mexico. The Beaumont formation lies unconformably on the Lissie formation and is underlain unconformably by recent stream deposits of limited extent. The Beaumont formation is, in general, composed of plastic, poorly bedded clay, interbedded with lentils and occasional layers of fine sand. Stratification is very irregular. The clay as it appears near the surface varies from soft to stiff. The clay usually exhibits multiple slickensided surfaces that could be interpreted as evidence of shrinking and swelling cycles during the course of the deposition. The average composition of the Beaumont clay is about 60 percent clay, 20 percent silt, and 20 percent sand. Gravel as fractured rock is absent, but is represented as a particle size by larger calcareous nodules and concretions. The sand and silt of the formation usually occur mixed as silty sand, sandy silt, or sandy clayey silt. The sand is always fine to very fine in texture. Because of the irregular stratification of the Beaumont clay and the unconformity between the Beaumont and the Lissie formations, no regular stratification can be traced along the axis of the damsite. Generally, the dam rests on, and was built of, various phases of the Beaumont clay. Contact between the Beaumont and the Lissie formations is believed to occur within 30 feet of the surface at the locations of the outlet works structures.

Damsite Geology

The geologic conditions at the damsites of Addicks Dam and of Barker Dam closely follow the overall regional geologic setting outlined above. From the original ground surface, each damsite is overlain by sandy, silty, low plasticity clay to a depth of about 10 to 15 feet. This upper, relatively uniform and relatively impervious stratum is underlain by interbedded low plasticity clay (i.e., CL – including silty clay and sandy clay), silt (i.e., ML – including rock flour, and silty and clayey very fine sand with slight plasticity), and sand (i.e., SP, SM, & SC – including silty and clayey sand, and poorly graded sand). This interbedded stratum extends to a depth of about 30 feet and overlies high plasticity clay.

Outlet Works Geology, Addicks Dam. At the outlet works for Addicks Dam, the upper stratum of sandy, silty, low plasticity clay extends to the depth, as indicated above, of about 10 to 15 feet, or to about the depth of the original excavation for construction of the outlet works. This upper stratum is underlain by interbedded low plasticity clay (i.e., CL – including silty clay and sandy clay), silt (i.e., ML – including rock flour, and silty and clayey very fine sand with slight plasticity), and sand (i.e., SP, SM, & SC – including silty and clayey sand, and poorly graded sand). This interbedded stratum is highly variable horizontally as well as vertically. The erodible fine sand, silty fine sand, sandy silt, and silt occurs in interbedded layers and pockets throughout the stratum. This interbedded stratum extends to a depth of about 30 feet and overlies high plasticity clay. The lowest stratum consists of high plasticity clay with little silt or sand. A composite presentation of the soils profile and phreatic surface with key boring logs at the outlet works for Addicks Dam is shown as Figure 6.

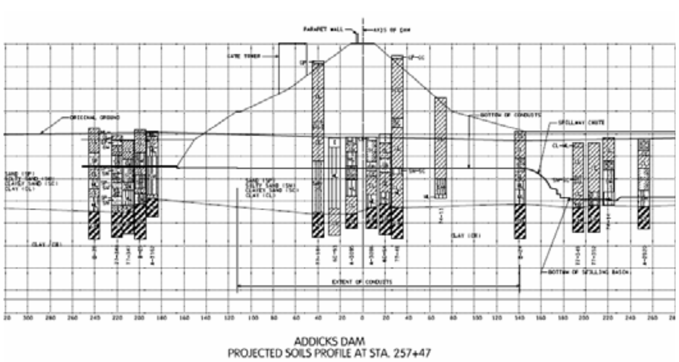


Figure 6 - Addicks Dam Soils Profile

Outlet Works Geology, Barker Dam. The geologic conditions at the outlet works for Barker Dam follows the general description for the damsites of Addicks and Barker Dams, but appears to consist of less sand and silty sand than at the outlet works for Addicks Dam. The upper stratum of sandy, silty, low plasticity clay extends to the depth of about 10 to 15 feet, or to about the depth of the original excavation for construction of the outlet works. This upper stratum is underlain by interbedded low plasticity clay, silty clay, sandy clay, silt, clayey silt, sandy silty, clayey sand, silty sand, and fine sand. This interbedded stratum is highly variable horizontally as well as vertically. The erodible fine sand, silty fine sand, sandy silt, and silt occurs in interbedded layers and pockets throughout the stratum. The sand below the outlet works at Barker Dam was encountered deeper in this interbedded layer than encountered at Addicks Dam. This interbedded stratum extends to a depth of about 30 feet and overlies high plasticity clay. The lowest stratum consists of high plasticity clay with little silt or sand. At the outlet works for Barker Dam, silt and sandy was encountered below the high plasticity clay. A composite presentation of the soils profile and phreatic surface with key boring logs at the outlet works for Barker Dam is shown as Figure 7.

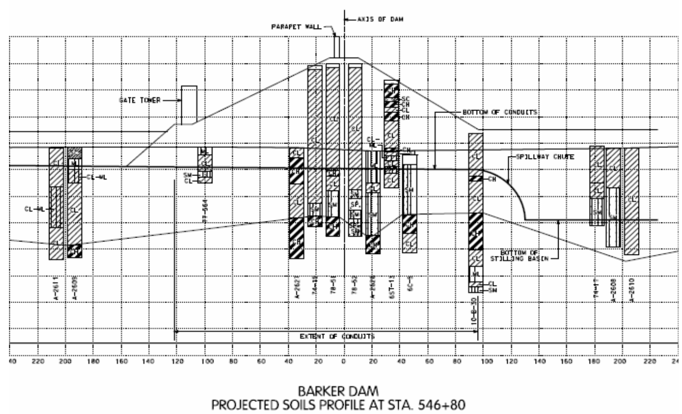


Figure 7 - Barker Dam Soils Profile

PROJECT HISTORY

Construction of Barker Dam was initiated in February 1942 and completed in February 1945. Construction of Addicks Dam was initiated in May 1946 and completed in 1948. Acquisition of all lands in Addicks Reservoir was completed in 1948 and in Barker Reservoir in 1951. As described above, the original design concept for both dams provided for four of the five outlet conduits to be uncontrolled, permitting a combined uncontrolled discharge of about 15,700 cfs into Buffalo Bayou. All conduits of both dams were gated by 1963 in order to restrict the combined downstream flow in Buffalo Bayou from both dams to the current non-damaging capacity of 2,000 cfs during normal operations. This combined discharge capacity is measured and monitored at a USGS gauging station at Piney Point about 9 miles downstream of the dams. Besides the above modifications, there have been several repairs and construction modification activities beginning during construction and continuing to present day.

Figure 8 - Outlet Spillway Construction in 1942, Barker Dam

Figure 9 - Outlet Conduit Floor Construction in 1942, Barker Dam

Foundation Erosion and Repairs, Addicks Dam. During the initial construction, a significant problem of the outlet works at Addicks Dam is related verbatim from an earlier document: "During construction of the structure some difficulties were encountered. The hard clay strata underlying the sandy material of the foundation caused seepage along the top of the clay all of which could not be picked up by well points especially during wet periods when seepage was sufficient to cause sliding and caving of the fine sand in the lower part of the side slopes of spillway and stilling basin excavation. This condition on 16 October 1946 during a wet period caused a slide which resulted in fatal injuries to a laborer. Although additional pumping from small sumps and drains in the excavation was maintained, neat excavation lines particularly of the lower slope of the spillway section monoliths 2 and 2A could not be maintained which resulted in the contractor placing additional concrete at his own expense to replace washed out sand. On 3 November 1946 a heavy rain, 4.85 inches, most of which fell between 6:00 PM and 9:30 PM, occurred which caused a large amount of sand to wash out from beneath the concrete foundation of the spillway. Repairs were made at the contractor's expense by placing 38⅔ yards of concrete in the washed out portions beneath the foundation and then drilling holes through the foundation concrete and using 108 sacks of cement to pressure grout remaining voids."

Spillway Cavity Repair, Addicks Dam. In 1968 a large cavity was discovered under the southeast cantilever wall base and the parabolic spillway slab. The cavity was assumed to have been caused by flow into upper weep holes, expansion joints, and cracks. The foundation material was apparently washed out through weep holes at the base of the spillway slab due to the lack of a properly installed filter preventing the foundation materials from exiting the structure. Investigations revealed that the cavity was extended under about two-thirds of the spillway slab and had a maximum depth of about 10 feet. Samples obtained from the bottom of the cavity through the weep holes revealed that the soils under the spillway slab range from sandy clay to silty sand with some sandy silt and clayey silt. Observations during these investigations revealed that the silty and sandy silt were readily transported by the flowing water and that the clay was being eroded by the flow of water. Figure 10 shows the spillway and stilling basin slabs of the original installation for Addicks dam. Expansion joint material between the spillway slab and cantilevered walls was replaced and the small crack in the toe of the east cantilevered wall was repaired. Figure 11 presents the typical arrangement of the expansion joints between the spillway slab and wall. Well screens were placed in the lower weep holes, and filter sand was flushed through the upper weep holes and some intermediate holes that had been drilled for the repair. After placement of the filter sand, the intermediate holes were plugged and relief valves were inserted into the upper weep holes.

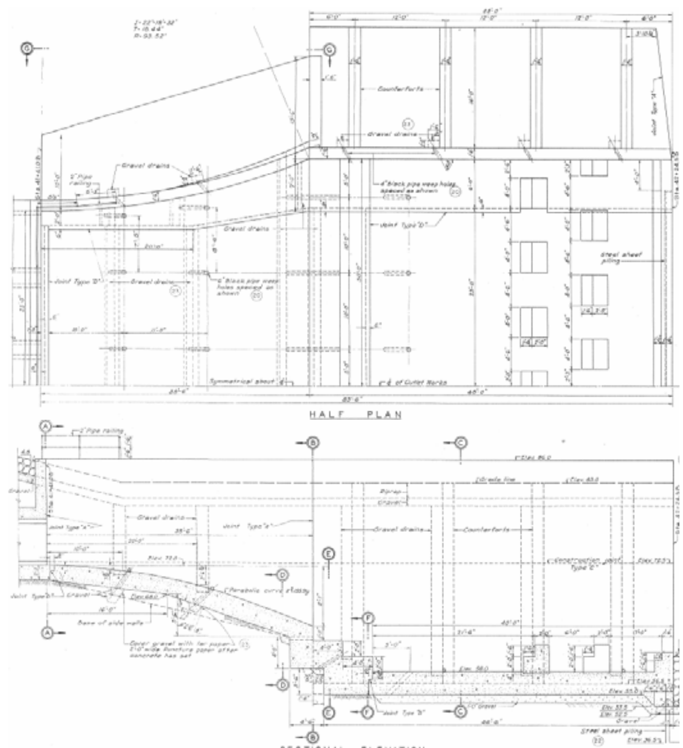


Figure 10 - Addicks Dam Spillway and Stilling Basin Slabs

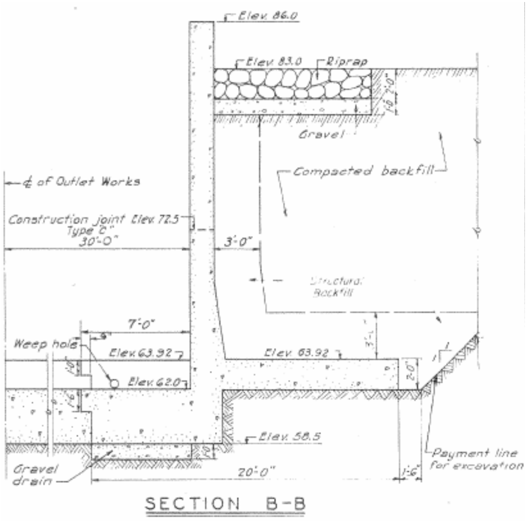


Figure 11 - Spillway Wall and Slab Cross-Section

Additional Repairs to the Cantilever Wall, Addicks Dam. In 1973, the measures taken in 1968 to repair the crack in the toe of the east spillway wall were discovered to be ineffective. Foundation material beneath the spillway wall and the spillway slab was still being lost through the crack Approximately 10 cubic feet of spalled concrete was removed from the cracked area. The existing reinforcing steel was cleaned, then Dow Earthfoam (joint filler) and sealant were used at the vertical and horizontal expansion joints. An epoxy binder was applied to the cleaned concrete surface prior to placing the replacement concrete. The eroded filter sand was replaced.

Remedial Seepage Control Measures, Addicks and Barker. In February 1977, seepage boils were discovered along the channel slope of the newly excavated Turkey Creek drainage ditch located below and parallel to Addicks Dam. Subsequent analyses and evaluations of the seepage potential at both Addicks and Barker Dam resulted in four contracts awarded to construct remedial seepage control measures at Addicks Dam and three contracts at Barker Dam. These works included construction of slurry cutoff wall and downstream stability berms along portions of the embankment, installation of clay blankets in upstream borrow areas, and other repair work at the outlet spillway area at both dams. As shown in the aerial map (Figure 12) that the slurry seepage control cutoff wall was installed across the outlet work conduit locations at both dams. However, the cutoff walls only penetrated the embankment to near the top of conduits and therefore leaving a window of seepage area around and beneath the conduits as shown in Figures 13 & 14. The works were performed during the periods of 1977 through 1979 and 1978 through 1982 for Addicks and Barker Dams, respectively.

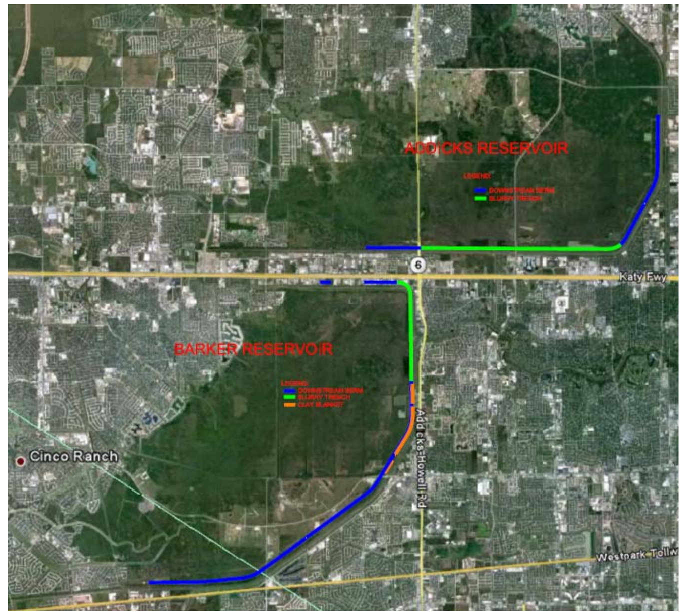


Figure 12 – Addicks and Barker Dams Seepage Control Measure Installations

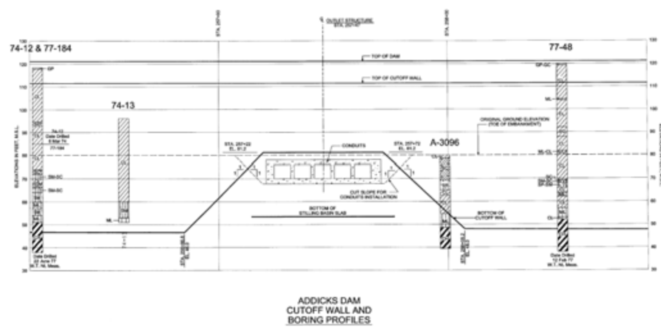


Figure 13 - Seepage Window Profile Around Conduits at Addicks Dam

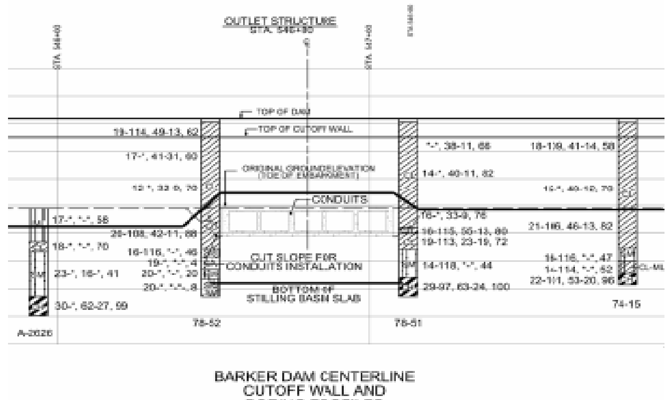


Figure 14 - Seepage Window Profile Around Conduits at Barker Dam

Additional Repairs to Outlet Works, Addicks Dam. Figure 15 shows how the conduit joints were constructed at Addicks dam. Inspections of the joints indicated that the filler or coatings between the joints have deteriorated. Repairs to the outlet works in 1979 consisted of sealing conduit joints. Repair works also included screening existing weep holes, adding weep holes in the stilling basin slab, adding relief wells, and backfilling beneath the spillway slab. Additional sealing, inspection and repair to relief wells, and additional replacement of filter sand, and repair of spalled concrete areas were completed in 1989.

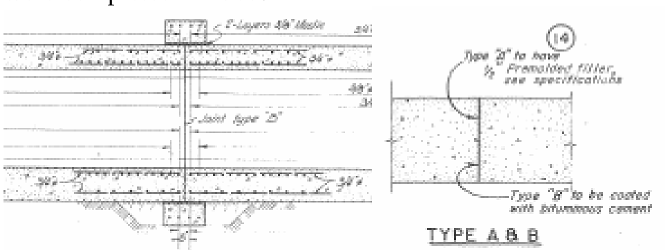


Figure 15 - Typical Conduit Joints For Addicks Dam

Repairs to Outlet Works, Barker Dam. Figure 16 shows the typical conduit joints at the Barker dam. Inspections of the joints also indicated repairs were required. Repairs to the outlet works in 1982 consisted of sealing conduit joints and installing additional weep holes and screens in the stilling basin slab. In 1989, additional repairs included sealing joints, inspection and repair of relief wells, repair of spalled concrete areas, and repair of stone protection.

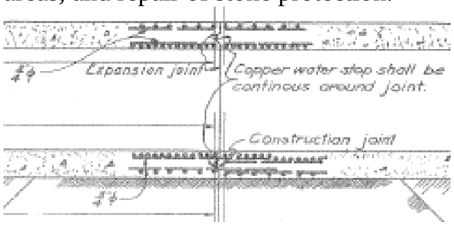


Figure 16 - Typical Conduit Joints for Barker Dam

Raising Top of Dam, Addicks and Barker Dams. Between 1986 to 1987, the tops of the dam embankments at both Addicks and Barker Dams were raise approximately 2 to 3 feet to provide a minimum of 3 feet of freeboard above the probable maximum pool elevation. This was an upgrade of the Addicks and Barker Dams to conform the Dam Safety Assurance Program with pertinent design criteria requiring raising the tops of the major segments of the embankments to achieve needed freeboard and providing erosion protection to the lowered ends of the dams so they could serve as overflow spillways storms greater than the Standard Project Flood (SPF) up to and including the Spillway Design Flood (SDF). At both Addicks and Barker Dams, raising of major segments of the dam embankment was accomplished by placement of additional materials over the existing crest and downstream side slope. The crest width of the enlarged embankment is 12 feet. The centerline of the raised embankment is offset 2 to 14 feet to the downstream side of the original centerline. A flexible-base access road was constructed on the enlarged embankment at each dam. At a segment between the outlet works of both dams, raising the tops of the dam embankments was not practical because this would have required steeper side slopes to compensate for the fixed dam width corresponding to the length of the conduits. Therefore, concrete T-walls (Parapet walls) were constructed on top of the existing embankment along these segments across the outlet works at both dams. The T-walls were offset 3 feet to the upstream side of the embankment centerlines and extended 420 feet along the crest of the embankments, which were not enlarged through these segments at the outlet works.

PROBLEM EVALUATIONS

Recent Foundation Investigations. There have been several major foundation investigations and studies in recent years. The following Figure 17 presents the timeline of the recent investigations and some response actions resulted:

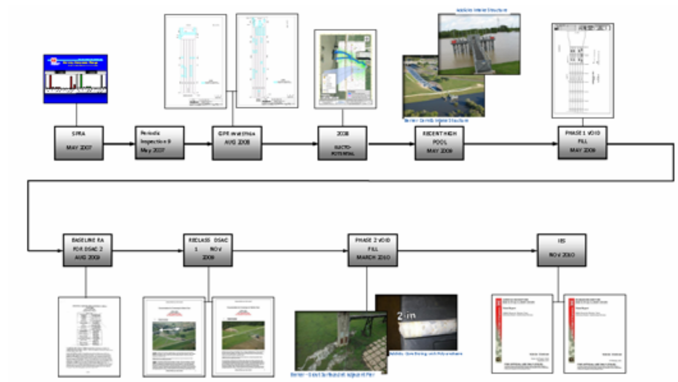


Figure 17 – Addicks and Barker Dams Foundation Investigation Timeline

Screening Portfolio Risk Assessment (SPRA). In May 2007, the USACE conducted a SPRA for Addicks and Barker Dams. The SPRAs were conducted nationwide on all USACE dams to assess risk and prioritize dam safety decisions and funding. These assessments assigned a Dam Safety Action Classification (DSAC) rating to each dam that is determined from a combination of potential risk and consequences and used for relative risk ranking. The SPRA resulted a rating of urgent for both Addicks and Barker Dams following the initial assessment due in part to potential for foundation seepage and piping under unusual events combined with the large population immediately downstream.

2007 Periodic Inspection. In May 2007, the USACE Galveston District also carried out Periodic Inspection No. 9 on both dams. Besides regular maintenance and repairs at the outlet works, the inspection also recommended detailed structural, geotechnical, and hydrological analyses to ascertain the condition of the dams due to signs of deteriorations of the outlet structure. The recommendations also included soundings along the conduits to determine if voids were present.

Ground-Penetrating Radar (GPR) Investigation. In August 2008, GPR investigations were conducted along the conduits of both dams to detect voids beneath the conduits. Figures 18 and 19 indicate the results, showing suspected voids from the interpretations of the GPR data.

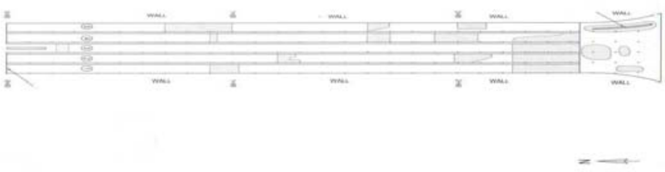


Figure 18 - GPR Anomalies Indicating Possible Voids, Addicks Dam

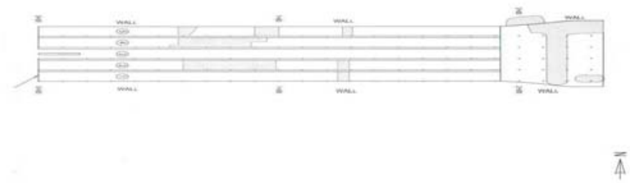


Figure 19 - GPR Anomalies Indicating Possible Voids, Barker Dam

Electric Potential Survey. In September 2008, a geophysical investigation using electric potential technology was conducted to study the seepage flow potential at the outlet works of both dams. The investigation concluded that seepage was believed to be flowing beneath the outfall conduits at Barker Dam. Figure 20 presents the results of this investigation at Barker Dam. The investigation also indicated that there was more mass flow and not a significant preferential seepage flow paths identified at the outfall of Addicks Dam.

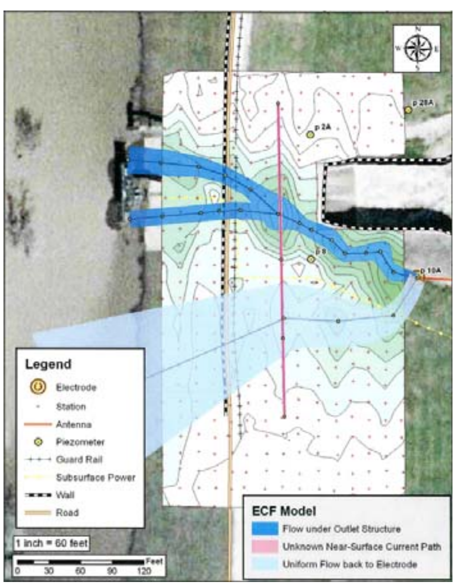


Figure 20 - Electric Current Flow Model, Barker Dam

Phase I Polyurethane Grouting. In May 2009, a near record high pool occurred at Addicks and Barker Dams. Due to the suspect of voids beneath the conduits of the outlet works from previously investigations, an urgent and compelling contract was executed to fill voids beneath the conduits. Because of the high pool and the anticipated seepage flows, it was believed that cement grout would not be effective. With this in mind, a hydro-insensitive polyurethane material was recommended for the grouting. Figures 21 and 22 show the grout volume fill recorded during the operations at both dams.

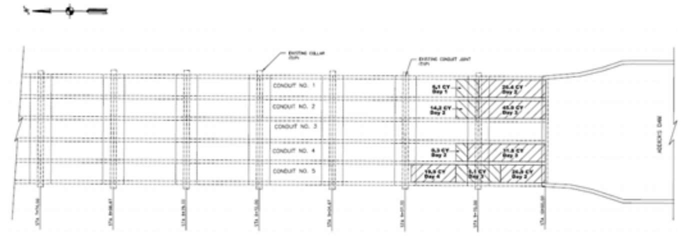


Figure 21- Polyurethane Material Grout Volume, Addicks

Figure 22 - Polyurethane Material Gout Volume, Barker Dam

Baseline Risk Assessment and Reclassification of DSAC Ratings. In August 2009, baseline risk assessments were performed to further investigate the risks associated with the potential failures at the dams. The studies found that risks associated with the PFMs were very high because of the dense populations through the Houston metropolitan areas downstream of the dams. Based on the further evaluation of the risk, the DSAC rating was revised to "Urgent and Compelling" for both Addicks and Barker Dams.

Phase II Voids Filling. Following the baseline risk assessment, USACE decided to follow up the polyurethane grouting with Phase II cement grouting to ensure all voids were effectively filled. In March 2010, Phase II cement grouting was initiated to fill all voids that might not have been filled during Phase I as well as additional voids that had been created since May 2009. Grout holes were drilled in the floor of the conduits the spillway and stilling basin as well as the outer walls of structure. Prior to initiation of grouting operations, the holes were probed to try and ascertain the depth of void beneath/behind the concrete. Voids were detected beneath the conduits, the spillway and the stilling basin. Figures 23 and 24 show the measured voids and the grout take volume beneath the structure during the Phase II grouting operations.

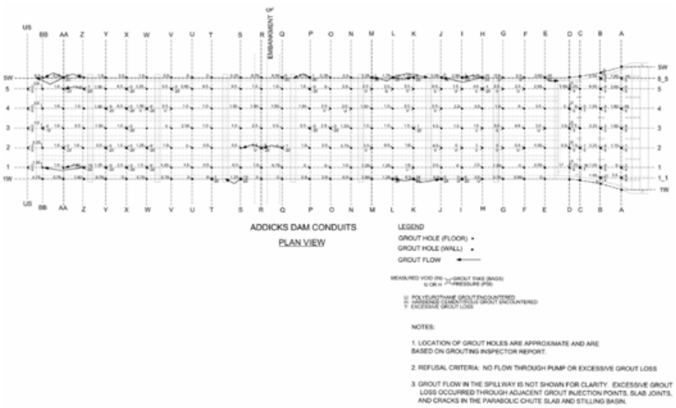


Figure 23 - Phase II Cement Grout Records, Addicks Dam

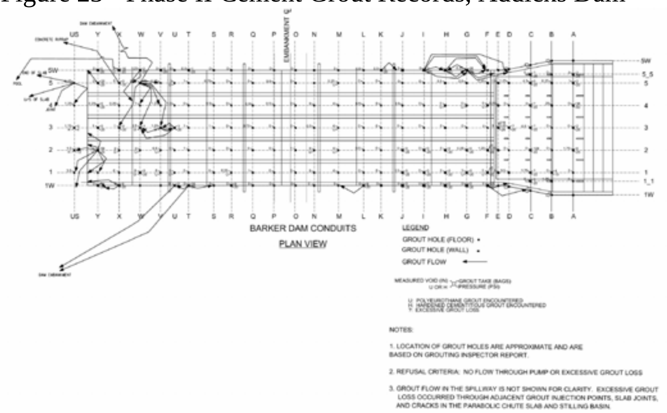


Figure 24 - Phase II Cement Grout Records, Barker Dam

Issue Evaluation Study (IES) by USACE. In May 2010, an IES was conducted using results from the 2009 PFM. The purpose of the IES was to evaluate dam safety issues in relation to the USACE tolerable risk guidelines and determine if the issues justified further actions either through interim measures, formal study or both in accordance with the ER 1110-2-1156. The cadre identified 22 and 23 Potential Failure Modes (PFMs) for Addicks and Barker Dams, respectively. Following their more detailed examination and discussion, six PFMs at each dam were determined to be significant failure modes for both Addicks and Barker Dams. Three PFMs were identical related to the outlet structure and include:

PFM 1 – Seepage flow along or beneath outlet works structure due to low stress areas leads to headcut erosion beneath outlet works structure. This failure mode is known to be credible because of the voids were discovered beneath the structures in 2009 and 2019 for both Addicks and Barker Dams.

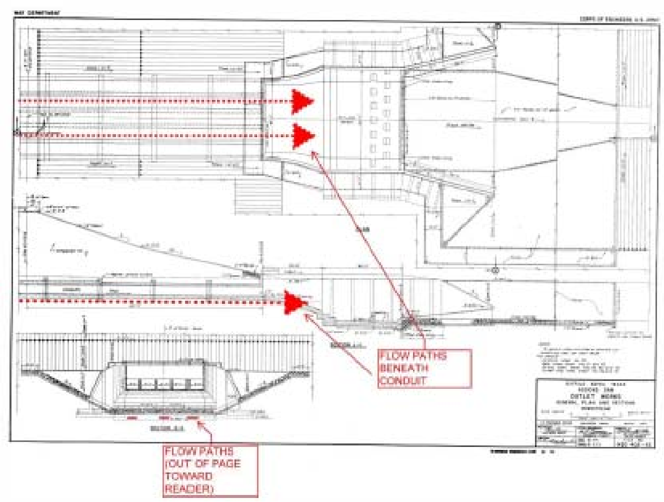


Figure 25 – Plan and Profile View of PFM 1

PFM 21 – Hydraulic pressure in the conduit exceeds pressure outside the conduit which leads to seepage through conduits joints and erosion along conduits. This PFM is credible because of the lack of effective waterstops in the joints on the conduits at both dams.

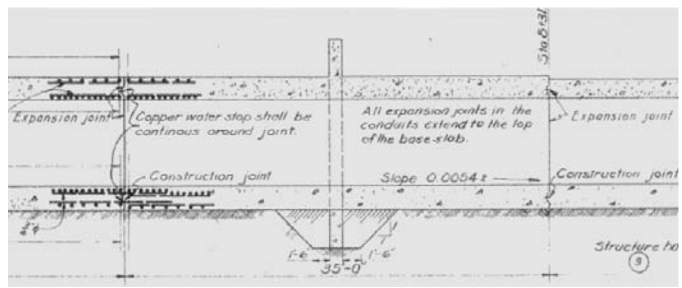


Figure 26 – Typical Conduit Joint Plan at Barker Dam

PFM 22/23 – Instability of the outlet works parabolic slab and stilling basin training walls due to uplift caused by excessive seepage and/or high tailwater. The uplift relief drains that were beneath the spillway and stilling basin were grouted during the 2010 Phase II grouting efforts. These drains were reestablished as point drains, but the relief is only provided at the location of the drain.

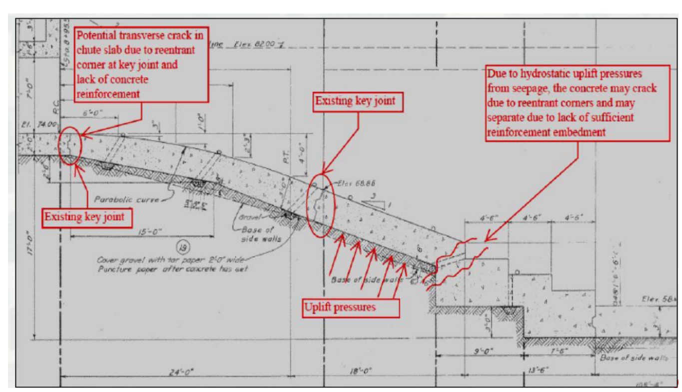


Figure 27 – Potential Uplift Pressure on Parabolic Chute Slab

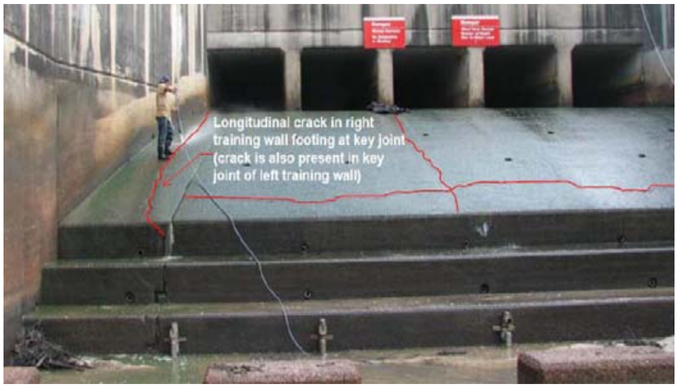


Figure 28 – Addicks Dam Parabolic Chute Slab with Existing Longitudinal and Transverse Cracks

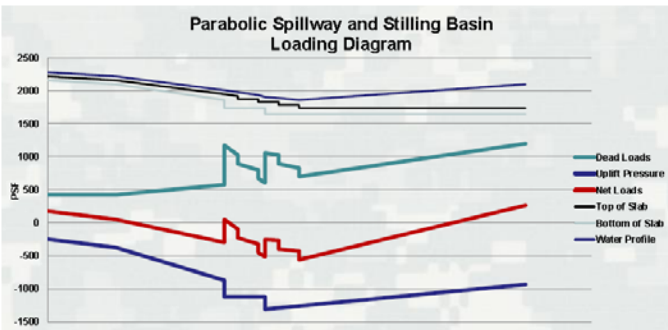


Figure 29 – PFM 22/23 Uplift Pressure Causing Instability to Outlet Parabolic Slab and Stilling Basin Training Walls

For Addicks Dam, a separate significant PFM related to the outlet structure was:

PFM 6 – Foundation seepage and piping beneath conduit or within the window where there is no cutoff wall as the cutoff wall rises and goes over the conduit leading to backward piping and erosion.

For Barker Dam, a separate significant PFM related to the outlet structure was:

PFM 7 – Seepage and piping in the foundation at the old Buffalo Bayou channel exiting at the end of the stilling basin, beneath the cutoff wall.

As part of the IES, a new baseline risk estimate was prepared by the risk cadre assembled by the USACE Risk Management Center. This baseline risk assessment identified potential failure modes that were judged to pose significant risk to the project.

Based upon the IES results, the issues justify further actions both through immediate interim measures and a formal Dam Safety Modification Study (DSMS) to formulate a risk management alternative plan consisting of a system of structural and/or nonstructural measures, strategies, or programs to meet, fully or partially, the identified DSMS risk reduction objectives subject to the constraints in accordance with ER-1110-2-1156.

INTERIM RISK REDUCTION MEASURES (IRRMs)

Shortly after receiving notification in 2010 from USACE headquarter that the Addicks and Barker Dams had been reclassified as urgent and compelling, the District began implementing IRRMs concurrent with beginning the DSMS. This IRRM plan partially addresses the potential failure modes, and only for the short term. The plan does not provide for an adequate seepage barrier or filter to prevent recurrence of void formation beneath the outlet work conduits and parabolic spillway. There are no interim measures available to effectively address the issues at the conduit joints. The IRRMs implemented between 2010 and 2012 included:

- Updated the District's Emergency Action Plan (EAP) for the dams and coordinated the plan with local authorities
- Conducted risk communications with public
- Installed a reservoir regulator alarm system for stage and rainfall reporting
- Filled voids under the concrete conduits
- Replace outlet structure gate at Barker
- Installation of outlet conduit monitoring instrumentation and enhanced lighting at the outlet structures
- Installation of a granular filter and inspection plugs at the conduits
- Created an Interim Reservoir Control Action Plan

LONG TERM SOLUTION ALTERNATIVES

In formulating the alternative plans, elements were first identified to address each failure mode independently then later effective elements were combined into alternative plans that address all failure modes. As many as 16 structural elements were initially screened for inclusion into one or more of 11 primary Alternative Risk Management plans.

Table 1 – Addicks & Baker Dams Alternative Risk Management Plans

ALT	DESCRIPTION	Elements Combinations
1	New Structure with cut-off and filter and remove existing structure. Includes: Cofferdam and diversion for new structure	1 & 9
2	New Structure with cut-off and filter and abandoning existing structure. Includes: Cofferdam and diversion for abandoning structure	13,14, 18
3	Cement-Bentonite Cut-off wall through conduits and Replace Outlet Works Slab and DS Walls	2, 16
4	Cement-Bentonite Cut-off wall through conduits and Replace Outlet Works Slab and DS Wall and Conduit Joint Repair	2, 16, 10
5	Cement-Bentonite Cut-off wall through conduits and Replace Outlet Works Slab and DS Wall and Conduit Joint Steel Liner	2, 16, 15
6	Upstream Cutoff Wall and replace Outlet Works slab and DS Walls	2, 10
7	Upstream Cutoff Wall and replace Outlet Works slab and DS Walls and Conduit Joint repair	2, 5
8	Upstream Cutoff Wall and replace Outlet Works slab and DS Walls and conduit steel liner	2
9	Jet grout cutoff wall and replace outlet works slab and DS walls	3, 16
10	Jet grout cutoff wall and replace outlet works slab and DS walls and conduit joint repair	3, 10, 16
11	Jet grout cutoff wall and replace outlet works slab and DS walls and conduit steel liner	3, 15, 16

Elements involving jet grouting through the conduit and an upstream cement bentonite cutoff wall were eliminated by a panel of experts from further considerations during the preliminary discussions/evaluations. Six Alternative Risk Management plans (6 through 11) were also eliminated since they were anchored by jet grouting through the conduit and an upstream cement-bentonite cutoff. Elements that involve downstream filter trench, removal of the stilling basin slab, conduit filter and replacement of the stilling basin walls were combined into a single element entitled “Stilling Basin U-frame Structure and Filter”. This left five remaining Alternative Risk Management plans that met the USACE policy requirements for final screening.

Alternative 1 involves constructing a new conduit and outlet structures with a seepage cutoff wall and engineered filter and removal of the existing structure at both Addicks and Barker. This alternative addresses all of the DSAC concerns and provides the most substantial reduction in risk but at the highest overall cost. For this reason and the fact that the residual risk is not substantially lower than Alternative 2, Alternative 1 was eliminated from further consideration.

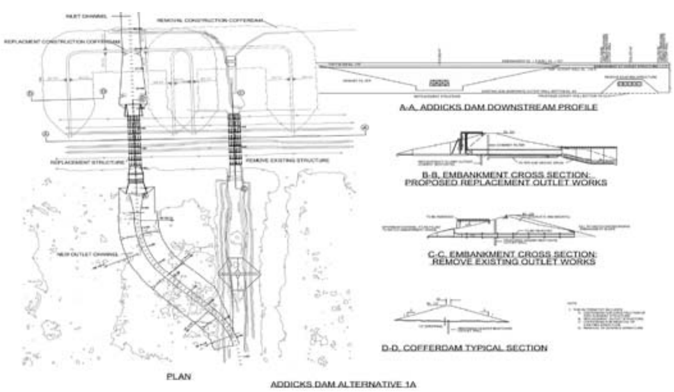


Figure 30 – Addicks Dam Alternative 1

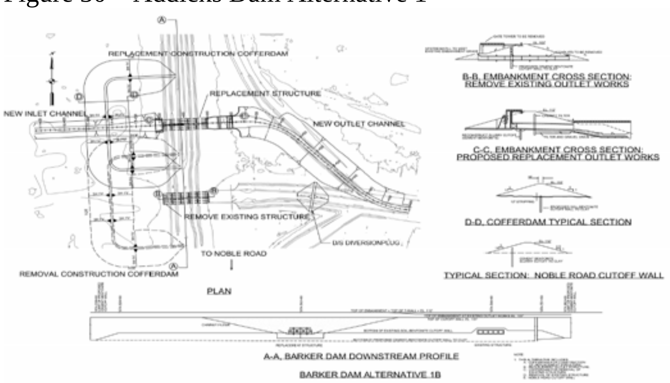


Figure 31 – Barker Dam Alternative 1

Alternative 2 consists of the same elements of Alternative 1 except the existing outlet structure will be abandoned in-place instead of removed. This alternative addresses all of the DSAC concerns and provides the second most reduction in risk due to some limited amount of residual risk associated with the existing outlet works. It is also the second most costly alternative evaluated.

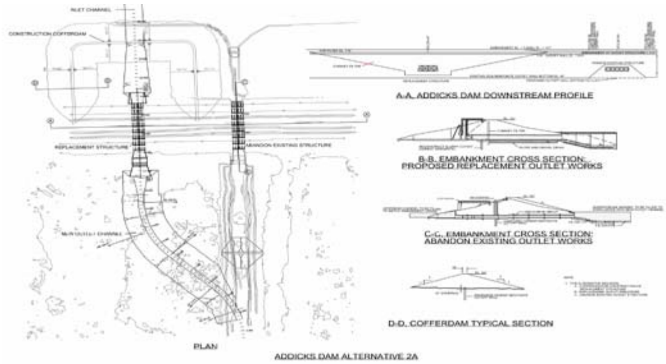


Figure 32 – Addicks Dam Alternative 2

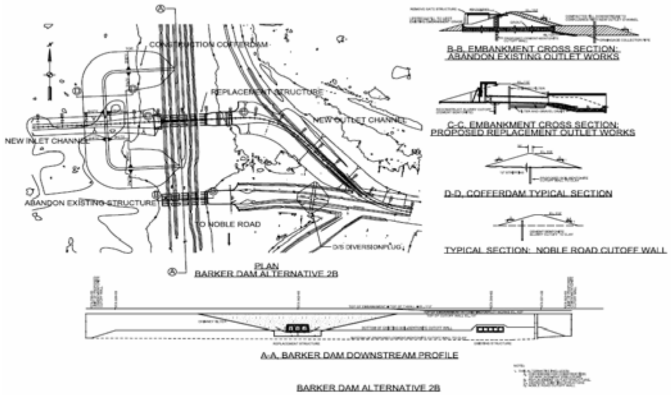


Figure 33 – Barker Dam Alternative 2

Alternative 3 provides for replacement of the existing parabolic spillway and walls with a U-frame structure and filter and construction of a bentonite-cement cutoff through the conduit. Additionally, it includes the seepage cutoff element at Noble Road for Barker Reservoir. This alternative reduces risk below USACE guidelines; however, it does not address long-term seepage and piping concerns within the existing conduit joints.

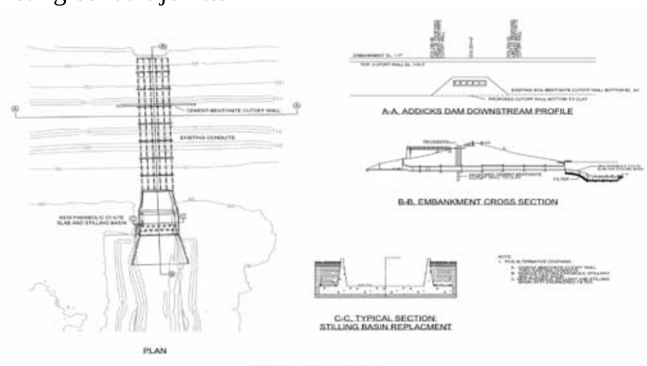


Figure 34 – Addicks Dam Alternative 3

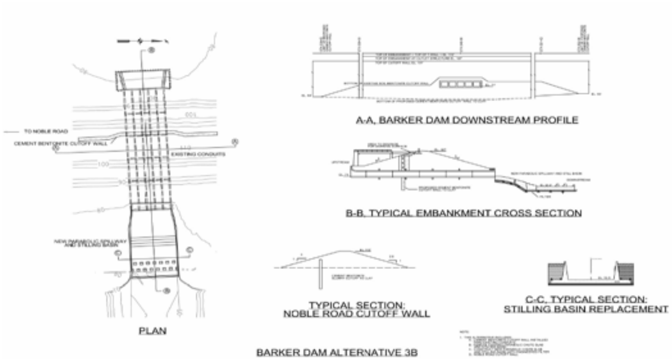


Figure 35 – Barker Dam Alternative 3

Alternative 4 involves replacement of the existing parabolic spillway and walls with a U-frame structure and filter, construction of a bentonite-cement cutoff through the conduit and conduit joint repair. Alternative 4 is the same as Alternative 3 with the addition of the joint repair. This alternative reduces risk below USACE guidelines; however, there is concern that the joint repair would not be robust and resilient.

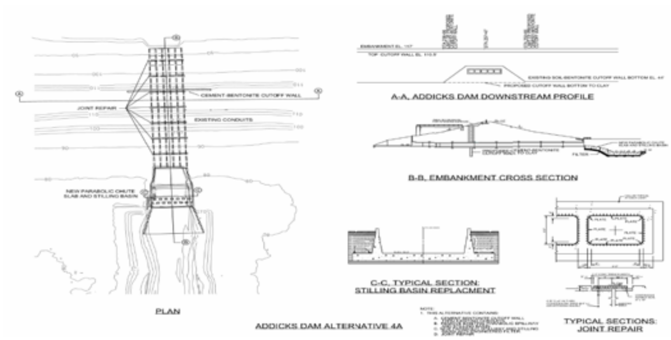


Figure 36 – Addicks Dam Alternative 4

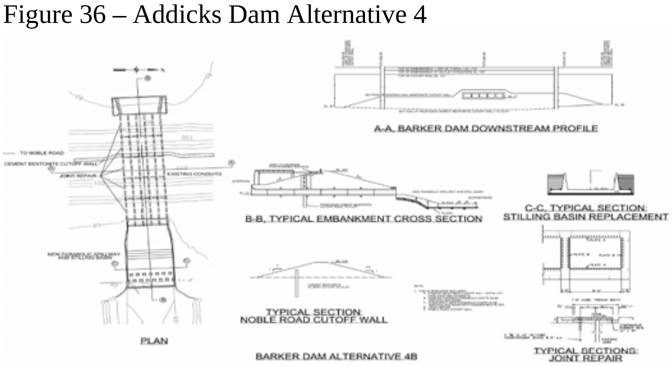


Figure 37 – Barker Dam Alternative 4

Alternative 5 is the same as Alternative 4 except a more robust welded steel pipe to function as a steel liner would be employed to address the long-term seepage and piping concerns associated with the existing conduit joints. This alternative addresses all of the DSAC concerns and provides the third most reduction in risk at the third highest cost.

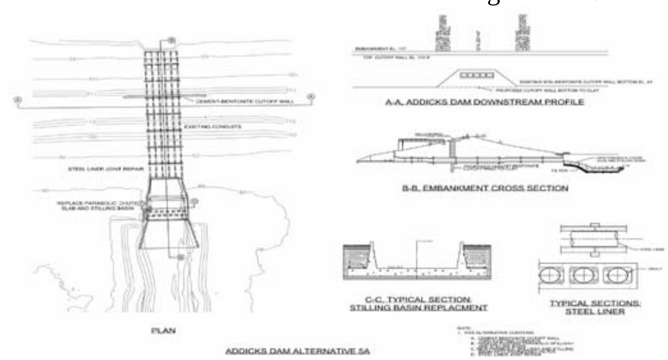


Figure 38 – Addicks Dam Alternative 5

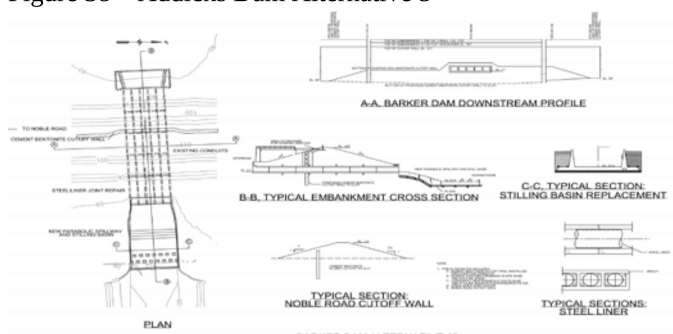


Figure 39 – Barker Dam Alternative 5

Based on detailed study of each alternative in regard to meeting the risk reduction guidelines, the cost of each alternative as well as the completeness, the acceptability, the effectiveness, the efficiency, the robustness, the redundancy, and the resilience of each alternative plan, Alternative 2 is the Recommended Plan. It consists essentially of constructing new conduit and outlet structures, including cutoff walls and engineered filters, and abandoning in-place the existing structure at both Addicks and Barker. Alternative 2 is recommended above all other plans considered for the long term operation of both Addicks and Barker Dams and is recommended to be fully implemented and constructed as soon as practicable in efforts to reduce current baseline risk below guideline.