ABSTRACT

The chain of six dams and reservoirs that make up the Highland Lakes along the Colorado River in Central Texas provide a case study in addressing evolving dam safety regulations, aging infrastructure and changing needs while continuing to provide flood control, water, power and parks for an increasingly urban population.

The Highland Lakes dams have provided many years of dependable performance. The LCRA operates these dams as designed to manage floodwaters, mitigating risk to people and property. The 85-year journey of the Lower Colorado River Authority (LCRA) to tame Texas’ Colorado River has been marked by four phases:

- **Mid-1930s-1950s** — Design, financing and construction of six dams and reservoirs
- **1940s-present** — Operation of dams, reservoirs, provision of hydroelectric power, water, flood control and parks
- **1989-2005** — Dam Modernization Program to bring all six dams into compliance with modern dam safety standards. The Modernization Program was completed in 2005, ahead of schedule and under budget.
- **2005-present** — Addressing the inherent risks that accompany infrastructure as it ages and the needs for public safety, water, and natural areas by the burgeoning Central Texas population.

Future performance must be measured by different standards from those of the 1930s and must account for the effects of those years of service. This paper illustrates the LCRA's journey to address evolving dam safety regulations and aging infrastructure, and focuses on the Dam Modernization Program and the years following.
INTRODUCTION

LCRA began taming the Colorado River in Central Texas in the mid-1930’s. The goal was to control flooding and use the river as a productive resource for both water and hydropower. That goal was realized in the 1950s with completion of Wirtz and Starcke Dams.

The dams have provided a reliable water supply, flood control, and a renewable source of power production for almost eighty years. They supply water to serve a downstream population now exceeding one million people.

The National Dam Safety Program, developed by the U.S. Army Corps of Engineers, was adopted in 1972 as a response to numerous dam failures across the country. While the Federal Energy Regulatory Commission (FERC) is the federal agency charged with regulating all non-federal hydroelectric power plants, the FERC concluded in 1989 that LCRA dams would remain exempt from federal jurisdiction provided that they meet state dam safety guidelines. Therefore, the Texas Department of Water Resources (TDWR) and its successor, the Texas Natural Resource Conservation Commission (TNRCC), assumed regulation of LCRA’s dams.

LCRA, recognizing the effects of aging on the dams and changes in federal and state standards, developed the Dam Modernization Program with the simple objective of improving the dams to meet the new dam safety standards. The Dam Modernization Program, completed in 2005, lasted approximately fifteen years and expended just under 50 million dollars. In the ensuing decade, LCRA has been making operational and safety improvements to all six dams while complying with state regulations under

Figure 1. LCRA Dams

Buchanan, Inks, Wirtz, Starcke, Mansfield and Tom Miller dams form the chain of reservoirs now called the Highland Lakes. All six dams are categorized as “Large-High-Hazard” dams under federal and state regulations. This is the highest risk category assigned to dams and essentially means that all six dams must be able to safely pass the Probable Maximum Flood (PMF).
the guidelines of the Texas Commission on Environmental Quality (TCEQ), successor to the TNRCC.
DAM MODERNIZATION PROGRAM

All the Highland Lakes dams provide hydroelectric power, and help manage flood waters but Mansfield Dam is the only one designed for flood control. Lakes Travis and Buchanan serve as critical water supply reservoirs for the region. Four of the dams are mostly concrete structures, Buchanan, Inks, Starcke, and Tom Miller. The other two dams, Wirtz and Mansfield, also have large embankment sections.

All six dams are categorized as “Large-High-Hazard” dams. This is the highest risk category assigned to dams and means that these dams must be able to safely pass the Probable Maximum Flood (PMF). (PMF refers to a flood developing from the worst combination of hydrological and meteorological conditions for a particular site.) In the late 1970’s TDWR began a statewide safety evaluation of existing dams for the U.S. Army Corps of Engineers (USACE). The safety evaluation was different from an inspection program and it involved deciding which existing dams might experience a bigger flood than that for which they were designed. TDWR and its successor, TNRCC, concluded that two LCRA dams, Wirtz and Buchanan, were among the five highest risk dams in the state, according to their response to the PMF.

In 1989, after further inspections, engineering evaluations, and risk-based prioritization, LCRA created the Dam Modernization Master Plan. The risk-based prioritization, an innovation and a precursor to the portfolio risk management approach to dam safety commonly used today, provided the framework for improvements and upgrades. The Dam Modernization Master Plan had three phases:

- Phase I: Re-evaluation of PMF and preliminary structural analysis
- Phase II: Preliminary design of structural modifications, data research, engineering, and lab analysis
- Phase III: Implementation of recommendations, dam safety guidelines, emergency action plans, final design, and construction of modifications

LCRA spent the next few years further inspecting and evaluating all six dams both hydraulically and structurally under various flood conditions. LCRA applied state-of-the-art computer modeling for design storms to refine the PMF and system demands. This yielded significant costs savings while complying with state regulations. In addition, physical hydraulic model studies were used extensively to more accurately predict hydraulic performance, and provided significant project-savings-to-engineering-cost ratios.

INVENTORY ASSESSMENT AND CONCEPTUAL DESIGN

The Phase I and II assessments, which evaluated the dams’ performance during large storm events, including the PMF, revealed that four of the dams — Buchanan, Inks, Wirtz, and Tom Miller — could potentially be unstable for the 500-year flood or larger events. Mansfield and Starcke dams were found to be safe during the PMF event. Wirtz Dam was shown to have its earthen embankment overtopped by approximately 11 feet during the PMF. Buchanan Dam was determined to experience a stability risk at reservoir levels only a couple of feet above normal operating range.
The dams were prioritized into a construction sequence, and LCRA embarked on design and construction of approximately $50 Million of dam safety improvements in ten years. LCRA developed the following schedule to prioritize and refine the recommended improvements for the four dams identified as needing repairs.

- 1995-1996: Protect Wirtz embankment section
- 1997-1998: Anchor Wirtz gravity non-overflow and floodgate Sections
- 1998-2000: Anchor Buchanan gravity non-overflow sections, Anchor Inks spillway section
- 2000-2008: Strengthen sections at Miller
- 1995-2008: Formalize dam safety inspection guidelines

Wirtz Dam
The Wirtz embankment section had the highest priority on the Dam Modernization Project construction schedule. As little as six inches of water over the earth embankment dam could cause failure … and the PMF would bring 11 feet of water over the top of the dam. Even the 500-year flood would overtop the dam by more than two feet. In fact, the 1952 flood brought the reservoir (Lake LBJ) to its historic high of one foot below the top of the dam.

Wirtz Dam is located about five miles west and upstream of Marble Falls. The dam is a combination of concrete and earthen embankment. Near the powerhouse, concrete sections span the Colorado River bed. To the north of the powerhouse, the tallest part of the 4,000 foot-long earthen embankment stands 100 feet above ground. If water overtopped the dam, the safety of the spillway and non-overflow sections could become questionable too. Though the embankment section would likely fail first, the concrete sections would still be at risk.

Overtopping protection in the form of roller compacted concrete (RCC) was the most cost-effective solution to protect the embankment. The recommended stabilization for the concrete spillways and non-overflow concrete sections was post-tensioned anchors.
Buchanan Dam

When Buchanan Dam was completed in 1938, it was the largest multiple-arch dam in the world. While most people think of those big arches that stretch across the original Colorado River bed as the entire dam, there are other parts of Buchanan, and they required improvements in the Modernization Program. Studies showed that the arches were stable for global stability during PMF loads, but spillways and non-overflow sections had lower-than-required safety factors.

Both the spillways and non-overflow sections are “gravity” dams which get their strength from their size. The dam must weigh more than the force of the water behind it. However, in the 1930’s engineers did not fully understand the phenomenon of “uplift” and the importance of adequate weight to assure the reliability of the dam. Modern engineers know that water also seeps into the foundation rock and pushes up on the dam from the bottom and can cause the uplifted portion to move downstream, possibly carrying with it adjoining parts of the dam.
Today, dams are either so big that they weigh more and can resist uplift, or they have drains in the foundation to relieve uplift pressure. Two findings pointed toward lower than desirable safety factors at Buchanan. Parts of Buchanan Dam have no drains at all and, to make matters worse, the concrete in the dam weighs slightly less than expected. Therefore, the stability of the non-overflow sections was questionable at lake levels two feet above the normal level.

Two methods of strengthening the non-overflow sections were developed in the preliminary studies: LCRA could strengthen through the use of post-tensioned anchors or they could add more concrete to make the dam heavier for roughly the same cost. However, even after the non-overflow sections were strengthened, dam stability depended on 37 operational floodgates spread over three spillways. There were only four traveling hoists to operate 37 gates. The two northernmost spillways (small) each had only one hoist, and no backup generator while the south spillway (large) had two hoists. Preliminary recommendations were for adding one more hoist to each small spillway, so all spillways had two hoists each along with backup generators.

Inks Dam
Inks Dam, located five miles downstream of Buchanan Dam, is 1,548 feet long. Half of the dam is a non-overflow concrete powerhouse section similar to the one in Buchanan Dam. The rest of the dam is an overflow spillway that has no flood gates. Both parts are concrete gravity dams. Since LCRA built Buchanan and Inks dams simultaneously, the same types of problems existed at both dams.

The overflow spillway was fraught with leaks. The crest of the spillway is at elevation 888 feet msl. Almost every construction joint seeped water from Inks Lake. All of the joints were weak and computer models indicated that the top two layers of the spillway could potentially move downstream when the lake reached 908 feet msl.

Uplift pressure was also a problem in the foundation of Inks Dam. Although the dam had drains, they were not working well. Part of the overflow spillway could slide downstream when the lake level exceeded 910 feet msl. Most of the other half of Inks
Dam, the non-overflow section, would be stable even under PMF conditions. A small part of the non-overflow section could fail if the lake level exceeded 913 feet msl. However, the overflow spillway would fail first. The ensuing reservoir drop would reduce the instability of the non-overflow section. Thus, if the spillway were strengthened, the threat to the non-overflow section would emerge. The recommended repairs to Inks Dam were to strengthen the spillway and the non-overflow sections with post-tensioned anchors.

Tom Miller Dam
Tom Miller Dam is mostly concrete, with an overflow spillway and nine floodgates. An earthen embankment armored with granite blocks completes the left side of the dam. The LCRA successfully built the dam after two previous attempts by others had failed. Mansfield Dam contributed to this success by reducing the floodwaters reaching Austin. Computer models in the preliminary evaluation indicated that the problems at Tom Miller Dam could cause it to fail just above the 500-year flood level.

The overflow spillway at Tom Miller Dam is actually part of the first Austin Dam, covered with concrete. Pieces of the old masonry structure are still visible inside the dam. This part of Tom Miller Dam could potentially slide downstream when Lake Austin exceeded elevation 505 feet msl.

Next to the overflow spillway is the floodgate section. This section, considered a slab and buttress dam, is hollow and was first constructed as the second Austin Dam. When the LCRA rebuilt the dam in 1940, this part of the dam was strengthened and new floodgates added on top. The upstream face of the gated hollow section is a concrete panel, supported by a column anchored in the river bed. Four of these panels were built without support struts to act as expansion panels. These panels were considered overstressed without the support struts during the LCRA assessments.

A flood as large as the PMF could overtop Miller’s embankment section along the powerhouse. The overtopping would be about three feet and it would possibly cause the embankment to fail quickly.

The recommended repairs in the preliminary study were: post-tensioned anchors in the overflow spillway, column strengthening for the floodgate section, and a concrete parapet to prevent embankment overtopping.

FINAL DESIGN AND CONSTRUCTION
LCRA led a team of multiple engineering consultants, including independent peer review boards and academics to push forward with final design. Key aspects of the final design effort included comprehensive geotechnical investigations, physical hydraulic modeling, advanced finite element modeling, dam safety instrumentation design and monitoring, risk assessments, value engineering, and development of plans and specifications. The result was an optimized approach to dam safety.
improvements for various types of dams including multiple-arch, slab and buttress, gravity, earthen, and masonry dams that rest on hard, soft, and karstic rock.

**Wirtz Dam Embankment Overtopping Protection**

Since breaching of the embankment section was considered a likely event due to overtopping, LCRA placed the highest priority on this project. The main purpose of the project was to allow the dam to safely pass 100 percent of the PMF. This was achieved by armoring the downstream slope of the earthen embankment and constructing a stilling basin at the downstream toe to allow the dam to overtop safely during the PMF.

![Figure 8. Wirtz Dam, 1998](image)

The armoring and stilling basin were constructed of roller compacted soil cement (RCSC), modified from RCC after borings indicated an extensive source of good sand on LCRA property downstream of the embankment toe. A final design mix of sand, LCRA fly ash and Portland cement was developed from test sections established on site and observed for a period exceeding one year. Durability testing indicated the soil cement would be satisfactory for the overtopping project. This was a win-win for LCRA: they were able to dispense their fly ash byproduct and forego the expense of purchasing offsite materials for the mix. The contractor established a batch plant in the sand source area and was able to produce economical soil cement.

The final design incorporated a stepped spillway for energy dissipation during overtopping and a stilling basin was constructed below the existing toe so that it could be founded on solid rock. Hydraulic model studies were performed to substantiate the step geometry on the downstream slope and the stilling basin performance. The stilling basin was then backfilled with soil and the original toe contours were re-established. This soil is intended to wash out if the dam is ever overtopped. Otherwise it goes completely unnoticed to those unfamiliar with the construction work.

With more than 174,000 cubic yards of RCSC, this project is one of the largest embankment overtopping protection projects in the United States and the largest overtopping project using RCSC.
Wirtz Dam Anchoring Project
Detailed geotechnical investigations, rock testing, stability analyses, hydraulic model studies and finite element models provided an in-depth evaluation of stabilization alternatives for Wirtz Dam. Post tensioned anchors offered the most cost-effective method of stabilization, and the anchoring project for Wirtz started in 1998. The anchors selected were epoxy-coated strand to enhance corrosion protection. There were 92 anchors distributed along the spillways and the non-overflow powerhouse section. The anchors extended approximately 80 feet into solid granite and had bond zones of 30 feet. Inclinometers, tiltmeters, load cells, and other instrumentation were installed prior to construction to monitor any effects caused by the anchoring and then to monitor long term performance of the anchors.

Some lock-off slippage problems were encountered with the epoxy strands and were addressed by de-rating a few anchors and then adding additional anchors to establish the required stabilizing forces. The problems encountered with the epoxy strand moved LCRA away from the future use of epoxy coated strand.

The anchoring project was successfully completed in 1999 and dam safety instrumentation has indicated that the anchors caused no adverse movements of the spillway piers during construction and performed satisfactorily during the monitoring period.

Buchanan and Inks Dams Anchoring
LCRA moved their anchoring efforts to Buchanan Dam and Inks Dam in 2000. To expedite implementation, the work at the dams was bid as a single project and construction awarded accordingly. The anchor stabilization of the non-overflow sections at Buchanan Dam and the overflow spillway at Inks proceeded in general conformance with the preliminary report recommendations.

Physical model studies were performed at Inks Dam to evaluate hydrodynamic pressures during flood operation and resulted in a significant savings on the required anchoring. Anchors were uncoated strand and ranged from five strands to 24 strands.
The anchors extended 70 feet into granite and had 30 foot long bond zones. Altogether, seven non-overflow sections of Buchanan Dam were stabilized with 117 anchors and 46 anchors were utilized at Inks Dam spillway. Piezometers and extensometers were installed prior to construction to monitor any effects caused by the anchoring and then to monitor long-term dam performance. The construction project was completed successfully in 2001 and the dam safety instrumentation reported successful performance.

Tom Miller Dam Modifications and Anchoring
Considering that two dams had failed previously at the Tom Miller site, LCRA authorized an in-depth evaluation of the structure, including a probable failure mode analysis, breach analysis, flood routing, physical model studies, advanced geotechnical exploration, non-destructive testing, and advanced stability analyses. The Tom Miller Dam modification and anchoring project began in 2003, and only after a million-dollar access road was constructed in the downstream floodplain to allow construction access for the main dam rehabilitation.

Tom Miller also proceeded in general conformance with the preliminary report recommendations. The primary difference at Tom Miller was that there was no longer a granite foundation like the previous three dams. Tom Miller Dam is founded on karstic limestone. Prior to the anchoring of Tom Miller Dam, a test anchor program was performed to assess the potential problems associated with the karstic limestone on normal anchoring procedures. The work at the dam was completed in 2004 and included:

- Strengthening spillway rollways and upstream expansion slabs in the gated hollow section
- Adding a concrete parapet to prevent the earthen embankment from overtopping
- Adding stitch anchors along the stilling basin tie
- Installing 55 post-tensioned anchors in the overflow spillway and powerhouse section
- Correcting storm drainage at the north powerhouse entrance
- Adding dam safety instrumentation
BEYOND THE DAM MODERNIZATION PROGRAM

During the dam modernization program, the LCRA recognized that its ability to respond quickly to extreme rainfall and flood events was limited by the event recognition time, availability of personnel, and the type and number of hoists located at each dam. The LCRA initiated the addition of hoists at the dams with radial gates. The implementation of these operational improvements has been led and conducted largely by internal LCRA staff and resources. LCRA assigned the first and second priority for hoist additions to Wirtz Dam and Tom Miller Dam, respectively. The hoist addition projects for both dams were completed between 1998 and 2001. Buchanan Dam was third in the hoist addition program due to its more remote location and significant storage capacity.

In 2006, LCRA evaluated the potential effect of a localized extreme rainfall events at Buchanan Dam using current flood routing models and computational fluid dynamic models. The study revealed that additional hoists would be needed on two of the three spillways.

In June 2007 a severe rainfall event occurred in the immediate vicinity of Starcke Dam, a non-tainter gate dam just downriver of Wirtz Dam and relatively close to Buchanan Dam. The event produced over 19 inches of rainfall in the overnight hours and when crews were called out, roads were already closed and the access road to Starcke Dam was washed away. This event reinforced the need for a quick response to a severe localized rainfall event at any of the LCRA dams and the potential benefit of remote operational capabilities of the spillway gates. Thus, LCRA embarked on providing twenty six (26) new hoists to Buchanan Dam.
As a result of the dam modernization program, LCRA implemented a rigorous dam safety inspection in compliance with state and federal guidelines. The dam safety program includes annual inspection and comprehensive facility reviews at regular intervals. The comprehensive facility reviews highlighted the need to evaluate the structural capacity of the tainter gates. In turn, the structural analyses identified the need to bring the spillway gates at Buchanan, Wirtz, Mansfield, and Tom Miller Dams into compliance with modern gate design standards and improved operations.

In 2007, LCRA elected to start the tainter gates improvements at Buchanan Dam due to their level of overstressing at normal pool. The LCRA developed a completely new dewatering system, necessary to safely work on the gates, and required that the system be deployable in flowing water to save the reservoir in the event of a gate failure. In 2011, LCRA began an eight year project to rehabilitate the 23 unique ‘Paradox’ flood gates located within Mansfield Dam. The gates are being removed from the dam for the first time since they were installed in 1938. They will be completely refurbished along with adding some minor modifications to provide better operation. LCRA is also currently in the planning stages of refurbishing the nine tainter gates at the Tom Miller Dam and will continue on to the Wirtz Dam where ten more tainter gates will be refurbished.

CONCLUSION

LCRA has now been steward of the six Highland Lakes dams for over 80 years. They are actively engaged in maintenance of and improvements to their entire dam system. Responding to the changing needs and safety standards, LCRA has funded almost $100 million of improvements in the past 20 years. They are steadfast in their goals but maintain flexibility when needs arise. As a result of its efforts, West Regional Awards of Merit were awarded to the Lower Colorado River Authority (LCRA) for its outstanding commitment “to do the right thing” in its multiple roles as a provider of water and electric services, flood protection and community services. LCRA was also awarded the Texas Public Works Association Award for Project of the Year under the Structures category.
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