To fulfill the potential of the City of Waco's Lake Brazos, a labyrinth weir replaced the gated spillway on the Brazos River. The labyrinth weir was constructed on a flowing river over the foundation of the existing dam without expanding the dam's footprint or rerouting the river during construction—at nearly half the cost of earlier estimates.

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Despite the problems with the lake levels, significant growth had taken place along the banks of the Brazos. Private development along the river included apartments, waterside restaurants, and floating restaurants. Baylor University expanded along the western shoreline, and the City of Waco invested in many improvements along the river, including parks and miles of promenades along the riverbanks. But faced with continuing operational problems, unreliable lake levels, dangers to maintenance workers, and costs of $50,000 to $100,000 annually for maintenance and repairs, the City of Waco embarked on a mission to alleviate the problems associated with the dam. Earlier plans to replace the dam had called for the expenditure of $30 million, posed a significant threat to the environment, and required diverting the river channel. In 2004, at the city's request, engineers with the Austin and Fort Worth offices of Freese and Nichols, Inc., resurrected a passive structure concept from among earlier assessments.

The city established these goals for the project:

- Reduce the construction costs and environmental harm contained in earlier proposals.
The design and construction of the staggered labyrinth weir met the city's goals through the following:

- Studying and evaluating the risks of the hydraulic challenges;
- Developing a phased construction program using the foundation of the existing dam;
- Developing a plan to manage the river during construction.

The phased construction plan and the use of cofferdams eliminated the major environmental effects common to dam replacement, which derive from channel diversion and the construction and siting of a new dam. This plan reduced the cost and duration of the construction.

Research at Utah State University's Utah Water Research Laboratory conducted using partial- and full-width scale models confirmed that a labyrinth weir could offer satisfactory performance during submergence conditions while maintaining upstream lake levels. The research also validated the suitability of phased construction for minimizing disruption of lake levels and diverting river flows.

Frustration over the inability to maintain a steady lake level had been voiced loudly and repeatedly, and attempts over the years to correct the problems had not been satisfactory. Various city officials and the design team addressed this frustration by making presentations on the advantages of a labyrinth weir to civic groups and the Waco City Council. The design team faced questions about every facet of the proposed labyrinth weir from representatives of the city council, the Central Texas Branch of ASCS Texas Section, the Greater Waco Chamber of Commerce, Kiwanis clubs, and other groups, and the team made numerous presentations describing the research that had been carried out demonstrating that a labyrinth weir could perform on the site as proposed, that there was no need to construct a dam at another site, and that the budget and timetable could be met.

One important stakeholder concern—namely, the pledge to maintain normal lake levels during construction—was addressed through a schedule of lake lowering to which all parties agreed. The system of cofferdams managed both to maintain the lake during most of the construction period and to pass the floodwaters experienced in March 2007.

The site of the Lake Brazos Dam presented challenging hydraulic conditions. While the weir would eliminate the troublesome gates and maintain the normal pool impoundment, the site's rapidly rising tailwater level created a submergence condition for floods larger than the 10-year event. This meant that the configuration of the labyrinth weir had to provide optimal capacity at low heads while maintaining satisfactory performance at large heads.
In addition to handling the tailwater levels, the configuration of the labyrinth weir had to remain within the footprint of the existing dam both to avoid the need for extensive river channel modifications and to facilitate environmental permitting and reduce mitigation requirements. To achieve the labyrinth length required to handle the river flows, the labyrinth would replace both the existing gated spillway and the overflow embankment.

The labyrinth weir replaced a gated spillway and overflow embankment on the Brazos River near Waco's downtown, eliminating operation and maintenance problems that had plagued the spillway gates. The new, 3,000 ft (914.4 m) long labyrinth weir was constructed in phases within the footprint of the existing dam to conform to regulatory requirements and reduce costs. The design incorporates an upstream shift across the labyrinth near midstream. The left labyrinth has 13.5 cycles with walls 12 ft (3.66 m) high extending 307 ft (93.57 m) to the channel midpoint and rests on drilled piers within the area of the overflow embankment. The right labyrinth has 11 cycles with walls 20.5 ft (6.25 m) high extending 240 ft (73.15 m) to the channel midpoint and rests directly upon a portion of the existing stilling basin. Construction was performed in two phases corresponding to the left and right labyrinth sections to eliminate costly river diversions and to manage normal river flows and potential flooding. The final construction cost was $16,373,502, and construction was completed in 706 days.

Placement of the labyrinth on the embankment area resulted in an upstream shift across the labyrinth near midstream. Because of this shift, the labyrinth was considered unorthodox, and this was an important reason for developing the hydraulic model study.

Studies to assess the hydraulic performance of the labyrinth spillway included developing a refined hydraulic model of the Brazos River through Waco and physical modeling of the labyrinth weir, including conditions during construction. First, the team developed a mathematical hydraulic river model to estimate tailwater levels below the Lake Brazos Dam and to assess the effect of the labyrinth weir on upstream water levels. Then physical modeling was performed at the Utah Water Research Laboratory. Physical model testing included sectional and full-width models for both the existing and the proposed structure. Fourteen sectional and two full-width models were evaluated for the project. The results of the study have been published.

While the advantage of a labyrinth over a straight weir is that it increases the discharge capacity for the same channel width by increasing the weir centerline length, this hydraulic benefit decreases as the upstream reservoir level rises significantly above the design head. For a large head, cross flows from adjacent weir walls mix, reducing weir efficiency. The hydraulic capacity of the labyrinth weir is further affected by the rapidly rising tailwater resulting from the large head. Weir efficiency progressively decreases with increasing head to the point where the discharge over a labyrinth weir approaches the discharge over a linear weir with a broad crest. Any design for the Lake Brazos Dam had to address this situation, and the team had to demonstrate that the design would provide optimal capacity at low heads while performing satisfactorily at large heads with tailwater submergence.

The physical model study assisted in determining the following:
- Suitable labyrinth cycle dimensions and wall crest shape;
- Sequence of construction effects on river flows;
- Effect of temporary cofferdams;
- Upstream channel configurations;
- Downstream channel configurations.

The sectional models made it possible to test variations of individual labyrinth weir cycle geometry. Such parameters as wall angle, wall width, cycle width, cycle depth, apex shape, and crest shape were evaluated, and in each case the effects of tailwater submergence on discharge capacity were considered. Ultimately, the selected cycle configuration consists of a compact cycle with a wall angle of 8 degrees and rounded apices. The cycle wall has a thickness of 2 ft (0.61 m) and is topped with an ogee-type crest.

One advantage of the selected configuration is that the compact cycle with small wall angles provides a significant amount of effective weir length in a relatively small area. This made it possible to reuse the existing dam footprint while maintaining significant discharge capacity. A second advantage is that the ogee-type crest provides increased discharge over conventional crest shapes, providing the better performance at low flows needed to limit upstream nuisance inundation during normal river flows.

On the basis of sectional model results, the team ultimately selected a 25-cycle labyrinth design that would maintain the Federal Emergency Management Agency upstream inundation levels. The left labyrinth has 13.5 cycles within the footprint of the overflow embankment, and the right section has 11.5 cycles within the footprint of the gated spillway.

The full-width model confirmed hydraulic results from the sectional models, including submergence effects, and made it possible to evaluate the offset between the labyrinth sections. The
The physical model proved critical in assessing the project approach and provided important information on the performance of the labyrinth weir during construction, particularly because the 3,000 ft (914.4 m) long weir was constructed within the existing dam's footprint. The team planned the work in such a way that the construction would be performed in phases and that cofferdams would be used to accommodate river flows and maintain a full reservoir during construction. As a result of the hydraulic studies, the construction documents emphasized strict tolerances for the labyrinth wall profile and finish during construction and provided for risk sharing between the owner and the contractor in the event of flooding at the construction site.

Key areas of the construction phase evaluated with the full-width model were as follows:

- Sequence of construction effects on river flows and discharge rating curves for temporary conditions;
- Effect of temporary cofferdams;
- Upstream channel excavation and grading;
- Downstream channel configurations.

On the basis of these numerous evaluations, the team developed the following approach and sequence to minimize cost and manage the river:

- The left labyrinth would be constructed first.
- The left labyrinth would be constructed upon a new concrete platform occupying the footprint of the overflow embankment.
- The sheet-pile cutoff at the left labyrinth could be extended and used as a cofferdam if desired by the contractor.
- The existing hydraulic gates would remain operable during construction of the left labyrinth.
- An upstream scour protection concrete slab would be constructed on the south end of the left labyrinth to address scour issues brought to light during the hydraulic modeling.
- Work would start on the right labyrinth only when the left labyrinth was completed and river flows could be passed over it.
- The hydraulic gates could be blocked and flashboards added to serve as a cofferdam for work on the right labyrinth if the contractor determined that this was preferable.
- The right labyrinth would be constructed upon the existing roller-compact concrete foundation of the gated structure.
- Very tight construction tolerances would be required on the entire labyrinth to ensure that it performed as intended.
- City-approved lake lowerings would be accommodated at certain times to facilitate specified work items.

The model studies yielded information for the final parameters necessary for the development of the project construction documents. The modeling indicated that the river could be managed in stages consistent with the two distinct segments of wall anticipated for the construction of the left and right labyrinth weirs. Modeling also highlighted the need for temporary upstream scour protection to handle flows created by blocking half the river.

The construction schedule for the Lake Brazos Dam specified three phases for constructing two distinct sections—the left and right labyrinth weirs and a number of miscellaneous improvements. The phased construction was developed to accommodate the city's requirements to maintain lake levels and manage river flows.

As the project design evolved it became apparent that passing on all risks associated with managing the river to the contractor would result in much higher construction bids. Contractors would have to cover the unknowns with inflated bids in order to manage the known risk of working in the river. The design team worked closely with the city and developed a program for sharing the risk. The city purchased special insurance through the contractor to insure the work against flood damage and to mitigate risk costs. The key features of the risk sharing incorporated into the project documents were as follows:

- Cofferdam: A minimum elevation was specified for the cofferdam, and the top elevation was left to the discretion of the contractor.
- Lost time: The contractor was respon-
600 calendar days, and the expected final completion date was September 24, 2007.

Constructing the labyrinth crest to the very tight tolerances set forth in the project documents required intense effort and field verification. The contract documents called for the as-built crest profile to match the drawing profile within 1/4 in. (3 mm) when measured normal to the surface. The as-built crest elevation had to be within 1/4 in. (6.4 mm) of the elevation shown in the plans.

Numerous discussions involving the contractor and the design team focused on these tolerances, including considerations of entrapped air, which could cause a vuggy surface without proper attention. It was also realized that setting the forms properly would require careful surveying. Archer Western elected to use metal forms with removable top crest forms for the walls. In a test placement of a wall crest section, Archer Western demonstrated its proposed forming and finishing techniques. The test section was a success, and the firm developed a quality control plan to achieve the specified tolerances for the wall and crest construction.

The wall construction process involved setting the vertical wall forms to specified lines, grades, and elevations. The crest forms were then bolted on top of the wall forms. The concrete placement proceeded through the 5 in. (127 mm) wide continuous slot in the crest forms. After filling the forms, the crest concrete was given approximately two to four hours to set, after which the crest forms were removed from the green concrete. Concrete finishesers rubbed and floated the green concrete to the specified profile. This eliminated all the vugs from entrapped air and provided a right, smooth finish, thus ensuring proper hydraulic performance.

Construction work on the left labyrinth weir began on January 2, 2006, after an initial lake lowering scheduled to last four months. This lowering made it possible to construct the temporary cofferdam system and to make upstream channel improvements. During this initial lake lowering, the contractor was also able to complete the foundation system for the left labyrinth weir. As part of the environmental control plan, environmental boom lines were installed around the work areas, and all waste collected during construction was taken to landfills or approved disposal sites.

With lake levels back to normal pool by early May 2006, construction continued on the remaining elements of the left labyrinth weir, including the platform slab, the labyrinth walls, the access driveway, the downstream impact slab, and the downstream riprap. Construction of the left labyrinth weir was substantially complete in early October 2006, three months ahead of the next specified lake lowering.

Given the early completion of the left labyrinth, the intermediate lake lowering, which was originally scheduled for January 2007, took place during the first two weeks of October 2006. The intermediate lake lowering facilitated the removal of temporary cofferdams on the left labyrinth weir and the installation of temporary cofferdams for construction of the right labyrinth weir. With removal of its temporary cofferdam systems, the left labyrinth weir was put into service. The first spill over the left labyrinth weir occurred on October 31, 2006.

Construction work on the right labyrinth weir began as its cofferdam system was installed during the intermediate lake lowering. Right labyrinth weir construction reached an advanced stage by January 2007, when significant work on the right outlet works began. The right labyrinth weir was substantially complete by early March 2007, and substantial completion of the right outlet works was expected by the middle of the following month. As of early March, the project team was expecting final project completion in May 2007. However, river conditions changed dramatically in late March, significantly altering project completion.

During most of the project construction the Brazos River experienced low flow conditions owing to a statewide drought. Except on rainy days and days when the temperature was below freezing, the construction carried out between January 2006 and...
March 2007 had few interruptions. Then, as work on the right outlet works was nearing completion, river conditions changed. On March 29, heavy rains increased flows in the river from 4,000 cfs (113.3 m³/s) to 34,400 cfs (974 m³/s) in just 12 hours. Rain persisted in the area for the next few months and upstream reservoirs filled. The river flows at the site remained high owing to flood control releases on reservoirs upstream of the site, slowing construction. Work continued, but at a reduced pace.

During these days of high flows the risk management clauses in the contract documents became applicable. Despite the lost time, the contractor was able to recover some of the monetary losses thanks to the standby time conditions specified in the contract.

It was not until early August 2007 that river flows decreased sufficiently for work to resume at its normal pace. Given the extended severe weather conditions and high river flows, a project duration extension was granted and approved in accordance with contract documents, and substantial completion was delayed until October 2007.

The floods experienced late in the project provided a full-scale test of the left labyrinth performance and validated the hydraulic modeling expectations for the project during the construction phase. The right labyrinth weir withstood the high river flows with no structural damage, and the left labyrinth weir performed as expected.

The Lake Brazos Dam construction phase was very labor intensive, comprising 104,395 work hours. However, the construction safety performance for the project was excellent, and no time was lost because of accidents. The safety program included daily and weekly activities. The crews performed daily task hazard analyses, and the contractor’s project management team completed weekly safety audits. Safety aspects were considered in every task performed by crew members.

With river flows back to manageable levels, the contractor began preparing for project completion. A final lake lowering was scheduled for mid-October so that the right labyrinth weir cofferdams could be removed and final work items could be completed. The entire labyrinth weir was declared substantially complete on October 31, 2007. The first spill over the entire labyrinth weir occurred on November 7, 2007. The project was declared officially complete on January 8, 2008, two years after the notice to proceed and with an actual duration of 706 days.

The dam was dedicated on November 13, 2007.

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**PROJECT CREDITS**

**Owner:** City of Waco, Texas

**Engineer:** Freese and Nichols, Inc., Fort Worth, Texas

**Prime contractor:** Archer Western Contractors, Arlington, Texas

**Geotechnical investigation and quality control testing:** Kleinfelder, Waco, Texas

**Topographic survey:** All County Surveying, Inc., Temple, Texas

**Corrosion evaluation:** Corpro Companies, Inc., Houston

**Peer reviews:** Eric B. Kollgaard, P.E., Concord, California; Henry T. Falvey & Associates, Inc., Conifer, Colorado; John A. Focht, Jr., P.E., Houston; and Tullis Engineering Consultants, Logan, Utah

**Quality assurance testing:** Fugro Consultants, Inc., Waco, Texas

**Bathymetric survey:** Hydrographic Consultants, Ltd., Bellaire, Texas

**Aerial mapping:** Surdex Corporation, Chesterfield, Missouri

**Physical modeling:** Utah Water Research Laboratory, Utah State University, Logan