Roller-Compacted-Concrete Dams: Design and Construction Trends

A review of the design and construction of five recently completed roller-compacted-concrete dams in the U.S. reveals that many new design details and construction methods have been adapted to enhance the final product.

By Fares Y. Abdo

Roller-compacted concrete (RCC) continues to gain recognition as a competitive material for building new and rehabilitating existing dams. Over the past two decades, many design details and construction methods have been adapted to enhance the final product while maintaining the speed of construction that provides RCC its competitive edge.

More than 370 RCC gravity dams higher than 50 feet have been built worldwide using RCC, 43 of these in the U.S. Many more RCC gravity dams less than 50 feet high have been built worldwide.

The first two large RCC gravity dams in the U.S. — Willow Creek in Oregon and Upper Stillwater in Utah — were built in the 1980s. These dams experienced seepage through lift joints and at shrinkage cracks. Since that time, design engineers, owners, and contractors have been looking for innovative methods to improve durability and aesthetics of RCC and to limit seepage. Several fac-

Fares Abdo, P.E., is program manager for water resources with the Portland Cement Association. He provides technical support and develops literature on roller-compacted concrete and soil-cement for water resources applications.

Using RCC for U.S. dams

In the late 1970s, promising research results led the U.S. Army Corps of Engineers to change the design of Willow Creek Dam in Oregon to RCC. Originally, the Corps planned to build a rockfill embankment dam. About a month later, the U.S. Department of the Interior’s Bureau of Reclamation adopted this new technology for its Upper Stillwater Dam in Utah.

Thus, RCC emerged as a viable new type of dam. The first to be completed was Willow Creek Dam, in 1982. At this dam, 433,000 cubic yards of RCC were placed in less than five months, at an average cost of $19 per cubic yard. The dam had no transverse joints and used a lean (low cementitious content) dry RCC mixture with nominal maximum aggregate size of 2.5 inches. Precast concrete panels were used on the upstream face, and the downstream face was unformed. Although Willow Creek Dam was deemed structurally sound, excessive water seepage at lift joints occurred during first filling of the reservoir.

A few years later, Upper Stillwater Dam was built. Construction of the dam began in 1985 and was completed in 1987. At 294 feet high and with a crest length of 2,673 feet, the dam required 1,471,000 cubic yards of RCC. As of September 2008, the dam remains the largest volume RCC dam completed in the U.S. Reclamation’s approach to building Upper Stillwater Dam was quite different from the Corps’ approach to Willow Creek Dam. Reclamation elected to use a richer RCC mixture (higher cementitious content) with a wetter consistency. The upstream vertical face and downstream stepped face of the central spillway section were slipformed using conventional concrete. The richer RCC mix produced a higher tensile strength and thus reduced the cross-section of the dam. In addition, the richer mix and the upstream conventional concrete facing provided better seals and prevented seepage at lift joints.

Upper Stillwater Dam did not include contraction joints. Vertical thermal cracks developed at an average spacing of about 190 feet. The cracks were not structurally significant; however, one crack produced excessive water leakage and required waterproofing repairs.2

Much was learned from the RCC dams built in the 1980s. Although these dams were never in structural jeopardy, future designs placed more emphasis on seepage and crack control for most projects. Designers of dams built during and after the 1990s incorporated different types of facing systems and control joints. They typically used richer RCC mixtures, a smaller maximum aggregate size, stricter construction requirements, special lift joint treatments, upstream membranes, and special facing mixtures to improve watertightness and bonding at lift joints.

Five recent medium-sized RCC dam projects

For the purpose of this article, medium-sized RCC gravity dams are those higher than 50 feet with a concrete volume not
exceeding 300,000 cubic yards. The five dams featured in this article were built between 2004 and 2008. The volume of RCC used ranged from 13,800 cubic yards to 218,000 cubic yards, and their heights vary from 70 to 188 feet (see Table 1). The dams are in Colorado, Georgia, Virginia, and West Virginia. In Georgia, deterioration from freeze-thaw cycles is of minimal concern. However, in the other three states, numerous freeze-thaw cycles take place annually. The main purpose of all five dams is to provide water supply for nearby communities.

New Big Cherry Dam in Wise County, Va., replaced a 70-year-old cyclopean concrete dam that suffered from structural deficiencies and had a spillway capacity less than that needed to meet the state dam safety requirements. In addition to increasing the spillway capacity, the new dam is 7 feet higher than the old dam, which increased the reservoir water storage from 359 to 633 million gallons.

Pine Brook and Genesee No. 2 dams in Colorado have similar designs, with a conventional concrete upstream face and an unformed downstream face covered with soil and vegetation. Both construction sites were congested, with minimal space for RCC plants, aggregate stockpiles, and RCC handling equipment. Pine Brook was the first design-build dam in Colorado, whereas Genesee No. 2 was built based on a negotiated contract with the lowest bidder. Most of the RCC aggregates for the two dams were mined and processed on site.

Hickory Log Creek Dam in Canton, Ga., about 30 miles north of Atlanta, began impounding water in January 2008. It is the tallest non-federally-regulated concrete dam in the state. Once filled, the reservoir will supply much-needed water especially after the region endured one of the most severe droughts on record, in 2007. The developer used crushed concrete aggregates hauled to the site from a nearby rock quarry.

Elkwater Fork Dam in Randolph County, W.Va., was built to supply water to Elkins, W.Va., and surrounding communities. The dam area is distinguished by its annual precipitation of about 60 inches, making it an ideal location for a water supply reservoir. RCC placement was completed in 2007, and the entire project is expected to be completed in late 2008. Again, the developer used crushed concrete aggregates hauled to the site from a nearby rock quarry.

### Table 1: Design Features of Five Medium-Sized RCC Dams

<table>
<thead>
<tr>
<th>Dam, Date of Completion</th>
<th>Height (in feet)</th>
<th>Length (in feet)</th>
<th>RCC Volume (in cubic yards)</th>
<th>Conventional Concrete Volume (in cubic yards)</th>
<th>Upstream Facing</th>
<th>Facing on Downstream Nonoverflow Section</th>
<th>Facing on Downstream Overflow Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elkwater Fork 2008</td>
<td>128</td>
<td>670</td>
<td>132,000</td>
<td>8,700</td>
<td>Precast concrete panels with PVC membrane bonded to downstream face</td>
<td>Formed RCC steps</td>
<td>Conventional concrete steps</td>
</tr>
<tr>
<td>Genesee No. 2 2007</td>
<td>103</td>
<td>360</td>
<td>50,000</td>
<td>3,000</td>
<td>Conventional concrete with water stops</td>
<td>Unformed RCC covered with earth and vegetation</td>
<td>Unformed RCC covered with earth and vegetation</td>
</tr>
<tr>
<td>Hickory Log Creek 2008</td>
<td>188</td>
<td>956</td>
<td>218,000</td>
<td>9,000</td>
<td>Precast concrete panels with PVC membrane bonded to downstream face</td>
<td>Grout-enriched RCC steps</td>
<td>Conventional concrete steps</td>
</tr>
<tr>
<td>New Big Cherry 2005</td>
<td>85</td>
<td>370</td>
<td>13,800</td>
<td>7,000</td>
<td>Conventional concrete with water stops</td>
<td>Conventional concrete steps</td>
<td>Conventional concrete steps</td>
</tr>
<tr>
<td>Pine Brook 2006</td>
<td>86</td>
<td>560</td>
<td>36,000</td>
<td>3,000</td>
<td>Conventional concrete with water stops</td>
<td>Unformed RCC covered with earth and vegetation</td>
<td>Unformed RCC covered with earth and vegetation</td>
</tr>
</tbody>
</table>

**Notes**

1This dam has a grout curtain. 2This is the only one of the five dams with a drainage and inspection gallery.

The downstream face of Pine Brook Dam in Colorado was made of unformed concrete that was covered with soil and vegetation. The dam has a conventional concrete upstream face.

The developer used crushed concrete aggregates hauled to the site from a nearby rock quarry.

### Dam design features

Table 1 summarizes the design features of the five dams. Some designs are simpler than others, which affected material cost and speed of construction, and consequently the project cost. The following sections offer specifics of the individual designs with respect to: galleries and foundation drains, grout curtains, facing systems, RCC mixtures, lift joint treatment, and contraction joints.

### Galleries and foundation drains

Only the tallest of the five dams, Hickory Log Creek, has a drainage and inspection gallery. The gallery is 18 feet downstream of the dam baseline and...
extends up the majority of the right and left abutments. The seepage collection system beneath a portion of the dam consists of sand and gravel trench drain discharging into the gallery. Flows from the gallery discharge into the stilling basin. At Elwater Fork Dam, drilled foundation drain holes are angled from the downstream toe of the dam to relieve uplift pressure in the foundation.

For the three smaller dams, designers elected to eliminate drainage galleries and foundation drains.

New Big Cherry Dam was designed to minimize long-term operation and maintenance concerns. One of the design objectives was to eliminate the drainage gallery, dam drains, and foundation drains. To provide adequate stability of the structure without these typical elements, a heel section was added to the dam. Pine Brook and Genee No. 2 dams also were designed to resist full hydrostatic uplift and thus the dams do not require foundation drains. Seepage through the dam foundations will drain to the downstream side.

Grout curtains

High in each abutment at Hickory Log Creek Dam, partially weathered rock with numerous seams of fine-grained materials was encountered. At these locations, 20-foot-deep concrete cutoff walls were installed. A double-row grout curtain was installed for the remainder of the foundation. The grout holes were spaced at 20 feet apart and were 25 to 80 feet deep.

At Elwater Fork Dam, the grouting program consisted of a single-line curtain at the upstream heel of the dam. Grout holes were drilled from a concrete plinth after RCC placement was complete. The holes varied from 20 to 80 feet deep.

Foundation seepage control at Pine Brook and New Big Cherry dams was limited to proper treatment at the dam/foundation interface. Excavations for the dams extended to foundation bedrock. The rock surface was cleaned and treated with dental/leveling concrete and/or grout before RCC placement. Additionally, Pine Brook Dam included a 10-foot-wide key 5 to 10 feet deep into weathered bedrock that serves as a seepage cutoff. At Genee No. 2 Dam, the design included a grout curtain that was installed after completion of the RCC placement. On the other hand, designers of Pine Brook Dam believed that a grout curtain could be installed after the dam was built if the seepage rate was larger than anticipated and presented a safety hazard or operational concern. However, as of September 2008, reports indicate that a grout curtain will not be needed.

Facing systems

As mentioned previously, some early RCC dams experienced significant seepage through lift joints and/or vertical cracks. As a result, many facing systems consisting of conventional concrete, precast concrete, geomembranes, and combinations thereof have been used and refined during the past two decades. Facing systems now are being used to reduce seepage and to improve durability and appearance. Detailed descriptions of the facing systems used worldwide can be found in a Portland Cement Association publication. A review of facing systems used on U.S. dams built after 2001 reveals that designers continue specifying facing systems that were successfully used during the 1990s.

As Table 1 shows, different types of facing systems were used on the upstream and/or downstream faces of these five dams. Conventional concrete with crack inducers and water stops at contraction joints were placed at the vertical upstream faces at New Big Cherry, Pine Brook, and Genee No. 2 dams. The slope of the downstream faces of these dams ranged from 0.88 horizontal:1 vertical to 0.75 horizontal:1 vertical.

The design of New Big Cherry Dam included an uncontrolled ogee spillway to function as a combined service and emergency spillway. The downstream face consisted of air-entrained conventional concrete for improved freeze-thaw resistance in a harsh environment. The spillway chute incorporated steps that provided energy dissipation.

The designs and construction of Pine Brook and Genee No. 2 dams were simplified by limiting facing systems to the upstream face and by eliminating the need for a concrete stilling basin to reduce cost. The dams were built without forming the downstream face of the RCC. Backfilling with earth to cover the unformed RCC was required after initial reservoir filling was complete. Each of these similar structures includes a concrete drop inlet and outlet works designed to pass normal flows. Larger flows up to inflow design flood can pass over an emergency spillway in the middle section of the parapet wall. The middle of the parapet wall is lower than the abutment sections to properly route the flood flow over the dam and down the vegetated earthen cover. Design engineers believed that a stilling basin was not needed based on anticipated flow characteristics and good-quality rock at the dam toe. To reduce initial cost, the owners accepted this design approach, knowing that if the emergency spillways operate, repair work likely will be needed to restore portions of the earthen covers.

The upstream face at both Hickory Log Creek and Elwater Fork dams is formed with 6-foot-high by 16-foot-long precast concrete panels with a geomembrane fully bonded to the downstream face of the panels. Each panel is anchored to the dam with six galvanized steel rods.

The downstream face of the chimney section at Hickory Log Creek Dam is built with decorative precast concrete panels without a membrane. The sloped downstream face is formed with 3-foot-high steps. The project team elected to
use conventional concrete placed concurrently with the RCC within the spillway chute and grout-enriched RCC elsewhere. Grout-enriched RCC gave the exposed downstream steps of the dam an improved appearance compared with typical exposed RCC. A grout mix was prepared using a colloidal mixing plant at the proportions of one part portland cement to one part water (by weight). After grading the RCC but before compaction, the grout was manually poured over the top of the freshly placed RCC adjacent to the downstream wood forms. Workers then internally vibrated the grout into the fresh RCC. The RCC in this area was compacted using flat bottom plate tampers, resulting in smooth, aesthetically pleasing exposed steps.

The downstream face at Elkwater Fork Dam is formed with 2-foot-high steps. Similar to Hickory Log Creek Dam, the spillway steps are conventional concrete. However, outside the spillway training walls, the steps are formed RCC.

**RCC mixtures**

Producing high-quality and uniform RCC requires good and durable aggregates and good quality control. For most projects, RCC aggregates are similar to conventional concrete aggregates meeting ASTM International C33 requirements. However, marginal aggregates that did not meet all standard ASTM requirements have been used successfully where the RCC is completely protected with an air-entrained conventional concrete facing system.1

Most of the aggregates for Pine Brook and Genesee No. 2 dams were mined on-site, whereas aggregates for the other three projects were transported from rock quarries meeting ASTM C33 quality requirements. The combined aggregate gradation for Pine Brook contained 2 percent or fewer particles smaller than 2 inches. For the other dams, a smaller maximum size was used for the aggregates.

Aggregate stockpiles at Elkwater Fork Dam were built during cold weather. This stockpile management and placement of RCC during the night shift avoided the need for cooling the aggregates while placing RCC during warmer weather.

Table 2 lists the mix proportions selected. All mixes used contained Type I/II portland cement except at Genesee No. 2 Dam, where Type II was used. Class F fly ash was also used for all five projects.

One RCC mix was used for each dam, except for Elkwater Fork. Due to sliding concerns during extreme loading conditions, a cutoff key at the heel of Elkwater Fork Dam was needed to achieve adequate safety factors. Mix 1 was used above the foundation cutoff key, and Mix 2 was used in the key.

Total cementitious materials in the mixes were 250 to 310 pounds per cubic yard, and the fly ash content was 37 to 60 percent of total cementitious materials. Generally, the cementitious contents of these mixes are higher than what was used in 1980s RCC dams but comparable to the mixes used in the 1990s. As compared to those used more than ten years ago, current mixes tend to be more workable, and some contain higher fly ash contents. For larger projects, most current mix designs specify a Vebe time of 15 to 30 seconds as was the case for Hickory Log Creek and Elkwater Fork dams. Vebe time is a test performed in accordance with ASTM C1170 to evaluate the workability of the RCC mixture.

Generally, design compressive strengths for RCC gravity dams specified during this decade are 1,500 to 2,000 pounds per square inch (psi) at ages 90 days to one year. It should be noted that the design/build team for Pine Brook Dam concluded that a design based on lower design strength and conservative cross-section would provide flexibility in aggregate selection and proportions. The owner’s concerns and permit restrictions made on-site aggregate mining and crushing very attractive. About 55 percent of the aggregates were mined on site. Shortly after the successful completion of Pine Brook Dam, on-site mining was also selected to produce RCC aggregates at Genesee No. 2 Dam.

RCC for the projects was mixed in twin, horizontal shaft, continuous pug mill mixers or in compulsory mixers. Mixer capacities were 200 to 500 cubic yards per hour. All-conveyor delivery systems were used at New Big Cherry, Hickory Log Creek, and Elkwater Fork dams. A combination of dump trucks and conveyor belts was used at Pine Brook and Genesee No. 2 dams. As has been the case for most RCC dam constructions, once on the lift surface, doz-
ers spread the RCC and vibratory rollers compacted the material in 12-inch lifts.

**Lift joint treatment**

Seepage control for these dams was provided by the upstream facing systems discussed earlier, as well as by adequate lift bonding and minimizing cold joints between RCC lifts. At Pine Brook Dam, cold joints less than 14 hours required no special treatment. Cleaning and washing the surface was required for joints 14 to 36 hours old. Older joints required bonding mortar to bond consecutive lifts. Bedding mortar mix consisted of 2,800 pounds per cubic yard sand, 500 pounds per cubic yard cement, and 300 pounds per cubic yard water.

Treatment of lift joints at Hickory Log Creek Dam was required, depending on the ambient temperature and the age of the compacted RCC lift. Horizontal surfaces exposed for more than 500 degrees-hours were considered cold joints and required spreading a 3/8-inch-thick bonding mortar layer just before placement of the new RCC lift. Cold joints older than 36 hours required pressure washing before spreading the bonding mortar.

**Contraction joints**

All five dams contained contraction joints. Generally, contractors used steel plates wrapped with polyethylene sheet to set up the joints. The steel plate is used to hold the polyethylene sheet at the desired location temporarily while the RCC is being spread. Immediately after spreading and before starting compaction of the RCC, the steel plate is removed, leaving behind the polyethylene sheet to serve as a bond breaker at the location of the contraction joint.

**Conclusions**

Economy and speed of construction continue to be the main reasons designers select RCC for new gravity dam construction.

Conventional concrete with contraction joints and water stops and precast concrete panels with bonded waterproofing membranes appear to be the upstream facing systems of choice for recently built dams. Conventional concrete and grout-enriched concrete are becoming more common for downstream facing systems.

Engineers continue specifying RCC mixes similar to those used in the 1990s, which have better workability and contain relatively higher cementitious contents compared to mixes used for RCC dams in the 1980s. High paste and very workable mixes containing fly ash in the range of 40 to 60 percent of total cementitious materials are commonly specified. Additionally, higher paste mixes with smaller aggregate (nominal maximum size of 1 or 1.5 inches) are selected to reduce segregation and achieve high density. Mixes with high fly ash content have been used on a few projects worldwide to build what is referred to as “all-RCC dams.”

The concept is to design a 100 percent RCC dam, and no other concrete mixes or auxiliary items are included to meet strength or seepage requirements. This concept, which would significantly increase the speed of construction, has yet to gain acceptance in the U.S.

Stockpiling aggregates during cold weather and placement of RCC at night can eliminate the need for costly methods that otherwise would be required to maintain the required mix temperature at time of placement. The stockpiling management approach used at Elkwater Fork Dam should be considered for RCC gravity dam construction.

Perhaps the most notable development in recent RCC gravity dams in the U.S. is the design approach implemented at Pine Brook and Genesee No. 2 dams. The following design features resulted in significant effects on the Pine Brook Dam speed of construction and total cost:

— Increasing the dam size to reduce the required RCC strength provided an opportunity to use on-site aggregates of marginal quality. Aggregates that fail to meet certain ASTM requirements still may be used if appropriate tests are performed and the results show that the aggregates can produce RCC meeting the project requirements;
— Building the dam without forming the RCC on the downstream face and covering the unformed RCC with soil provided protection against freeze-thaw action;
— Designing the dam to resist full hydrostatic uplift pressure eliminated the need for foundation drains and a drainage gallery; and
— Eliminating the construction of a stilling basin saved money and time.

Mr. Abdo may be reached at Portland Cement Association, P.O. Box 26381, Birmingham, AL 35260; (1) 205-979-9435; E-mail: fabdo@cement.org.

**Notes**