How Design/Build at Pine Brook Dam Dramatically Reduced Schedule and Costs

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SYNOPSIS. The design/build approach has been successfully used to expedite the design and construction process of many heavy civil construction projects, including bridges, highways, and multi-story buildings. One of its first applications for design/build in dams began when the Pine Brook Water District – a small water district serving only 400 taps or about 1200 customers, located two miles northwest of Boulder, Colorado (USA) – sought to build a new dam with an extremely aggressive schedule and budget. Given these constraints, Pine Brook believed a design/build approach was the only viable method to design and construct this new roller-compacted concrete (RCC) dam.

The design/build team implemented a process involving the owner, engineer and contractor at the earliest phases of the project. Geotechnical aspects, flood hydrology, RCC mix design, dam layout and constructability, seepage cutoff and collection, outlet works, instrumentation, construction schedule, and even aesthetics were evaluated by the entire team. This integrated team was able to quickly address issues and focus on preferred design elements without commissioning costly studies evaluating a myriad of alternatives. Design and construction were completed in only 18 months.

At the conclusion of the project the team believed they had saved considerable time and money, but comparing dam projects is difficult. The Genesee Dam in Colorado – a virtually a twin to Pine Brook in nearly every design aspect – was completed one year later at a cost nearly twice that of Pine Brook. The comparison of these two dams is a perfect illustration of the financial impacts of these innovations and is discussed with this paper.

INTRODUCTION

The Pine Brook Dam and Reservoir is a new dam built to store raw water for treatment and subsequent municipal use by the customers of the Pine

Brook Water District, located two miles northwest of Boulder, Colorado. The following figures show the project's location.

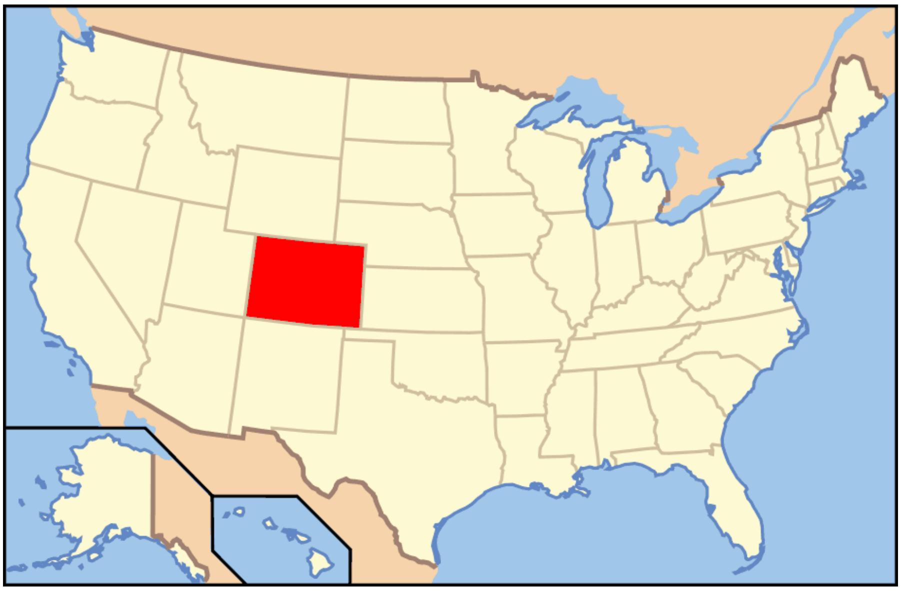

Figure 1. Colorado's Location within the USA

Figure 2. Location of Pine Brook Dam within Colorado

The dam is a roller-compacted concrete (RCC) structure approximately 86 ft (26m) high at its maximum section and 600 ft (183m) long along its axis. It retains approximately 100 acre-feet (123,300m^3) of water in a reservoir with a surface area of approximately four acres (1.6Ha).

NEED FOR PROJECT

The Pine Brook Water District was formed in the 1960s to provide treated water to residents of the Pine Brook subdivision. Located outside the city limits of Boulder, Colorado, the Pine Brook subdivision is at an elevation above that at which the City of Boulder provides a water service.

The Pine Brook Subdivision is located amidst the foothills of the Front Range of the Rocky Mountains. The terrain is mountainous, with many steep hillsides and ravines The Colorado region is semi-arid and receives approximately 15in (380mm) of annual precipitation, with the majority occurring in the form of winter snow.

Typical water distribution systems in the mountainous regions of Colorado involve diverting surface water flows from streams and rivers into storage reservoirs and distribution pipelines; diversions often involve transference of water over considerable distances through challenging terrain. Small community systems can be quite complex because of the need to divert and store water during high-flow periods (typically runoff of snowmelt during 2-3 months in late-Spring) and to also provide service during often lengthy late-summer and autumn periods where surface flows fall far short of water demand.

Complicating matters, water rights in Colorado are administered on a priority basis, meaning the older the water rights the higher the priority for their use. The Pine Brook Water District purchased some of the most senior water rights in Colorado, which include:

- Farmer's Ditch Water – A decree grants the district a 1 October 1862 right to divert 62.2 acre-feet (76,700m³) of water between 15 April and 15 October each year.
- Wellman, Nichols & Hann Water – A 1 June 1862 decree gives the district the right to divert 85 acre-feet (104,850m³) of water.
- Boulder White Rock Water – A 1 November 1873 decree gives the district the right to divert 11.3 acre-feet (13,950m³) of water in the summer and 11.8 acre-feet (14,550m³) of water in the winter.

Water is diverted from Four Mile Creek at Four Mile Canyon, a tributary of Boulder Creek approximately 2 miles (3km) from the Pine Brook Dam. It is pumped to Sunshine Canyon and then to Pine Brook Hills. Water from this pipeline is used to fill the reservoir. Water is withdrawn at an average of rate of between 150 to 200 gpm (9.5 l/s to 12.5 l/s), with peak flows of 1,000 gpm (63 l/s) required to flush the water treatment plant for short intervals.

Prior to undertaking construction of a dam and storage reservoir the District relied on several small storage reservoirs (concrete tanks) that only provided enough storage for four to five weeks of consumption.

Since 2002, Colorado has suffered from severe drought conditions. Prior to construction of the dam in 2005 the district had lost their surface water source due to drought on Four Mile Creek numerous times throughout the years. During 2002 Four Mile Creek was dry for 63 days straight.

In 2002 the drought created emergency conditions; residential customers were required to ration water and at the same time there was a high danger of wildfires, and inadequate water reserves for fire protection. The District therefore decided to immediately procure funding and embark on construction of a dam and reservoir to alleviate rationing of water.

Since the dam was built drought conditions have continued to prevail in the region and in 2008 and 2009 the creek has been essentially dry for nearly all of August and September. With the completion of the dam, the district has a full year's storage capacity when the reservoir is full.

SELECTION OF DESIGN/BUILD APPROACH

Because of the emergency conditions the District was faced with a very aggressive schedule. This, combined with budget constraints, Pine Brook determined that the design/build approach would be the most advantageous to complete this project. Pine Brook selected ASI Constructors Inc. (contractor) and TCB, Inc. (engineer) to accomplish this project, the first formal design/build dam project in Colorado.

The project began in January 2005, and involved the owner, contractor and engineer from the beginning. Representatives from the owner, contractor and engineer all attended and participated in regular meetings where key design elements were posed, debated, studied, evaluated, and refined. Issues such as RCC design strength, foundation issues, emergency and service spillway configurations, outlet works and other elements were discussed. Out of these meetings the project and its features took shape, and the design progressed until it was finalized in June 2005.

PROJECT DESIGN

Site Geology

The bedrock underlying the Pine Brook Dam and reservoir consists of the Boulder Creek granodiorite. This light grey, granite-like Precambrian rock is a medium-grained granodiorite to quartz monzonite. On the north abutment a 7 ft to 28 ft deep (2.1m to 8.5m) surface layer of colluvium overlies weathered and fractured granodiorite. The colluvium consists of clayey sand of loose to medium density mixed with silt and some gravel. The underlying weathered granodiorite is low strength, with an average unconfined compressive strength of intact rock of 6,000 psi to 7,000 psi or 41MPa to 48MPa. This weathered zone extends 25 ft to 42 ft deep (7.6m to 12.8m). Relatively fresh granodiorite underlies the weathered zone. The fresh granodiorite is medium strength, with an average unconfined compressive strength of 10,000 psi to 12,000 psi (69MPa to 82.7MPa).

At the centre of the valley a shallow surface deposit of alluvium and/or colluvium adjoins the creek bed and consists of clayey sand and gravel. The depth of this layer varies from a few feet to 18 ft (5.5m). A weathered bedrock zone underlies the alluvial deposits and continues down to a depth of approximately 40 ft (12.2m), where fresh granodiorite is encountered.

The surface soils on the steeper south abutment are relatively shallow – about four feet (1.2m) thick. There are scattered outcrops of the weathered granodiorite in this area of the dam footprint. The weathered rock zone is also shallow, extending to nine feet (2.7m) below the ground.

Historically, the area surrounding the proposed Pine Brook Reservoir site has been minimally affected by seismic activity. The largest earthquake occurred on 8 November 1882 near Greeley, Colorado. Its estimated magnitude was 6.2. A series of man-induced earthquakes began near Commerce City, Colorado, approximately 20 to 30 miles (12km to 18km) southeast of the Pine Brook site) during the mid-1960s. The team determined that a Peak Ground Acceleration (PGA) of 0.20g delivered from a 7.0- magnitude earthquake at a distance of 22 miles (35km) be used for seismic analysis of the Pine Brook facilities.

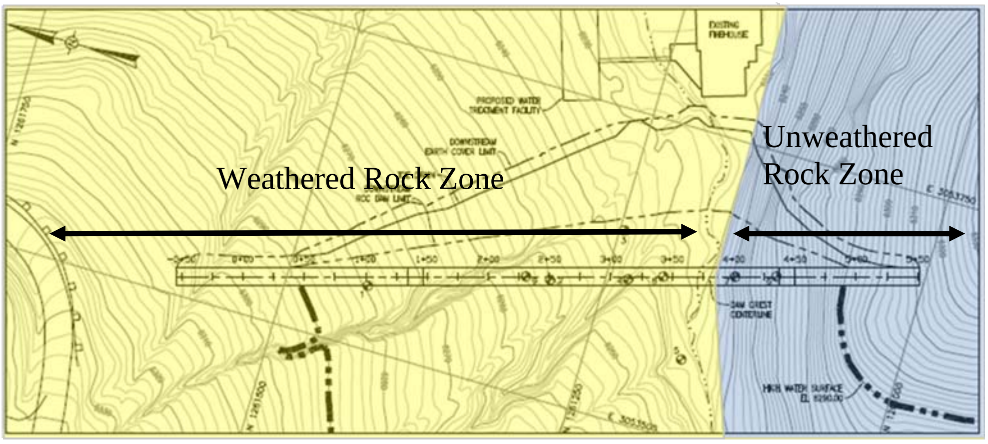

Figure 3. Generalized site geology

RCC STRUCTURE AND SPILLWAYS

The Pine Brook Dam is an RCC gravity structure. The dam is designed to safely pass the inflow design flood (IDF) equal to the probable maximum flood (PMF) event. The upstream parapet wall is designed to concentrate the flow during the IDF to the emergency spillway section, the central 290 ft (88.4m) of the dam. Appurtenant structures include a service spillway riser structure and conduit with an energy dissipater. An uncontrolled-drop inlet service spillway, located near the centre of the dam, passes flows up to 500 cfs (4.2m³/s) as a free flow condition and almost twice that under a pressure condition.

Approximately one year after initial filling of the dam, the downstream face of the dam was covered by a soil cover with a slope of 2H:1V (horizontal:vertical). The downstream soil cover was not incorporated into the structural design of the dam but was important for economic, environmental and aesthetic purposes. A chimney drain was constructed at the RCC/soil interface to collect, control and monitor seepage through the dam. The RCC structure is founded on bedrock, with a bottom-of-structure elevation of about 6210 ft (1892.8m) at the maximum section. A 10 ft deep (3.1m) key was excavated into the weathered bedrock below the base of the dam as a seepage cutoff. The downstream face of the RCC is unformed RCC and the upstream face is conventional concrete facing.

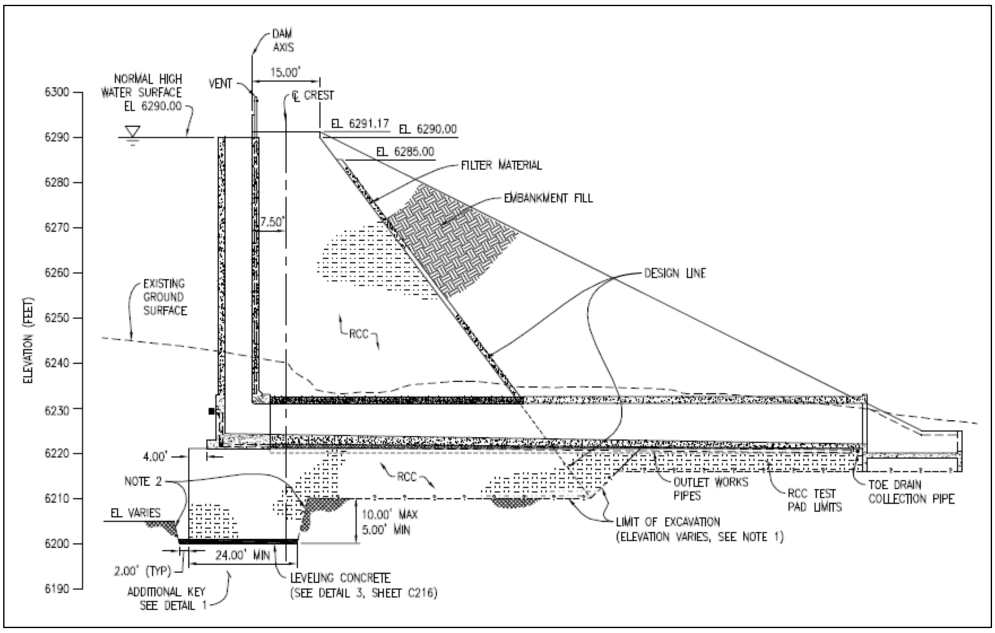

Figure 4. Typical dam cross-section.

RCC Mix Design

Stability analyses indicated that an RCC mix design with an ultimate unconfined compressive strength of 1500 psi (10.3MPa), tensile strength of 75 psi (0.52MPa), and cohesion of 300 psi (2.1MPa) would meet all stability and factor of safety requirements for concrete dams designed and constructed in Colorado.

Typical strengths for RCC dams are slightly higher than these values, primarily because higher strengths provide better long-term durability for the RCC. In the case of the Pine Brook Dam, the upstream face consists of a conventional concrete facing element and an unformed downstream face covered with soil. As such, an RCC mix with an ultimate unconfined compressive strength of 1500 psi (10.3MPa) was suitable and would meet long-term stability and factor of safety requirements.

The selected RCC mix consisted of 55% on-site-crushed coarse aggregate, 45% imported fine aggregate (Class 4), 160 lb/yd^3 (94.9 kg/m^3) of Type I/II cement, 100 lb/yd^3 (59.3 kg/m^3) of fly ash, and 234 lb/yd^3 (138.8 kg/m^3) of water. Lower design strengths combined with a conservative cross-section provided flexibility in aggregate selection and proportions. The District's concerns with importing aggregate and permit restrictions made on-site aggregate development very attractive, though not necessary. Space and budget concerns led to simple on-site crushing that produced a minimal base coarse grading of 2" to 3" minus (50mm to 75mm) that was blended with commercially-produced Class 4 base. After testing the initial mix, the team increased the cement and ash content slightly to provide greater insurance against the known variability of the crushed product.

Non-Overflow Section

The non-overflow section consists of a vertical upstream face, a 3.83 ft (1.2m) high parapet wall with a top-of-wall elevation of 6297.5 ft (1919.5m), a vertical "chimney" section with a width of 15 ft (4.6m) at crest elevation 6293.67 ft (1918.3m), and a 0.75H:1V downstream face.

Emergency Spillway Section

The emergency spillway section is similar to the non-overflow section. The 3.83 ft (1.2m) high parapet wall has a top-of-wall elevation of 6295 ft (1918.7m) and the crest elevation of the vertical "chimney" section is at 6291.17 ft (1917.5m). The emergency spillway crest is 290 ft (88.4m) wide at elevation 6295 ft (1918.7m). No stilling basin for the emergency spillway was designed. Though turbulent flow conditions are expected at the dam toe when the emergency spillway operates, foundation erosion or undermining is not expected. Stability analyses demonstrated that the dam will be safe for the PMF event without the soil backfill.

A 6 ft (1.8m) high and 0.5 ft (150 mm) deep low flow notch was constructed in the emergency spillway to focus low flows through the spillway at one location, so that they can be more easily identified and handled.

Figure 5. Upstream face of dam and emergency and service spillway.

Service Spillway

The service spillway is a drop inlet structure founded on RCC and anchored to the upstream face of the dam. The outlet conduit discharges flood water through the RCC dam and downstream soil cover to an energy dissipation structure at the toe of the downstream soil cover. The flow area of the drop inlet portion of the service spillway is 5 ft by 7 ft with a crest elevation of 6290 ft (1917.2m). The conduit through the dam is 7 ft by 7 ft cast in-situ concrete. It has an initial invert elevation of 6224 ft (1897.1m) and a slope of 1.5%. The outlet conduit is designed to discharge service spillway flows as open-channel flow up to 500 cfs (14.2m³/s). Flows between 500 cfs and 1,000 cfs (28.4m³/s) will flow through the outlet conduit under pressurized conditions. Flows in excess of 1,000 cfs (28.3m³/s) will be passed over the emergency spillway.

Outlet Works

The outlet works consist of the following:

- A 12-inch-diameter (305mm) emergency drawdown pipe with a butterfly valve attaches to the upstream dam face adjacent to the service spillway shaft. The valve is operable from the crest of the dam. Water discharges directly into the service spillway outlet.

- Two 6-inch-diameter (152mm) stainless steel pipes are attached to the service spillway tower with intakes at elevation 6260 feet (1908m) and 6229 feet (1898.6m) and gate valves at the downstream end of the pipes. There are no upstream guard gates installed for the outlet works.
- An inlet screen is installed at each intake.
- The outlet works are encased in concrete through the dam and soil blanket.
- Outlet works are controlled from downstream valves located at the water treatment plant, located near the downstream toe of the dam.

Figure 6. Service spillway on upstream face of dam.

Foundation Preparation

Foundation preparation and treatment under the dam consisted of the removal of all overburden and highly-weathered bedrock; removal of rock overhangs; shaping of rock foundation; rock cleaning; and dental concrete treatment of cracks and cavities of the rock foundation. In the central valley section and along the left abutment, the depths of weathered rock excavation varied between one and 10 ft (0.3m and 3m). In the right abutment section the depths of weathered rock excavation were less than five ft (1.5m).

No foundation drain holes or grouting were designed for this dam as the structure was designed to resist full hydrostatic uplift. Seepage through the dam foundation is collected with a toe drain, placed at the downstream toe of the dam. This toe drain discharges into the creek channel immediately downstream of the principal spillway stilling basin.

Figure 7. Foundation cutoff trench.

As with most new dams, the foundation can pose one of the greatest construction and design risks. The design plan included excavation of the foundation in stages to identify stable foundation material and determine the refusal point for the seepage cutoff wall. The ability to plan for this approach was a significant benefit of the design/build process. It also eliminated a considerable interim design phase that would have involved additional foundation exploration.

Seepage Control

The following provisions were made in the design to control seepage through the RCC:

- Continuous RCC placement allowed for adequate lift bonding and minimized cold joints between RCC lifts. Special cold joint treatment was used when the next RCC lift was not placed within a designated time period, or at the designed cold joint locations. Cold joints were designed for the following locations: at the top of the levelling concrete pad, at the bottom of the concrete encasement of the service spillway conduit, and at the water supply pipe.

- Crack-control notches were constructed on the entire upstream and downstream face of the structure to control crack formation on each side of the RCC contraction joints.
- RCC contraction joint locations were adjusted upon completion of the excavation based on the bedrock topography and major grade breaks encountered. A total of six contraction joints were initially planned, but a total of eight contraction joints were eventually installed.

Instrumentation

Instrumentation at the dam consists of two new permanent bench marks, four brass survey caps, and three standpipe piezometers in the RCC. The new permanent bench marks are concrete monuments founded in bedrock in the right and left abutments above the dam. Brass caps were drilled and grouted into the crest of the dam near the left abutment, right abutment, maximum section and the principal spillway crest to monitor future movements of the structure.

CONSTRUCTION

The design of the Pine Brook Dam was initiated in January 2005 and completed in June 2005, when it was submitted to the Colorado Office of the State Engineer for review and comment. In July 2005, prior to the State Engineer's approval, excavation activities were initiated and were completed in August. Comments from the State Engineer were received the last week of August and changes were incorporated and resubmitted on 15 September. The project was approved for construction on 22 September, and permanent concrete placement for the dam began the next week. Because the site is in a residential area construction was limited to one 10 hour work shift, with no night construction permitted.

In order to immediately cover and protect the moderately weathered bedrock anticipated at the left abutment, a top-down construction method was initiated at the left abutment. Excavation of the left abutment began near the crest elevation, continued down to the valley bottom and was then immediately covered with abutment concrete for protection. The seepage cutoff trench was excavated simultaneously. The relatively flat slopes of the left abutment (as flat as 5H:1V in places) also allowed for this excavation method.

The right abutment, which comprised less weathered bedrock than the left abutment, was also exposed, but abutment concrete was placed concurrent with RCC placement. RCC placement began in the last week of October and continued until the first week of December when RCC construction was suspended due to cold weather. RCC placement began again in March 2006 and construction was completed at the end of June 2006, 18 months after the initiation of the design.

Figure 8. Unformed downstream face and installation of toe drain.

PERFORMANCE

The Pine Brook Dam has performed extremely well since its initial filling in 2006. Seepage rates through the dam have been measured to range between unreadable to a maximum of 4 gpm (0.25 l/s). As expected the highest seepage rates occur when the reservoir is at or near the maximum elevation, but these rates are far below the anticipated rates of 15 gpm to 20 gpm (0.95 l/s to 1.25 l/s). These low seepage rates are especially encouraging given the lack of a foundation grout curtain. The lack of a grout curtain has resulted in piezometric pressures responding to changes in the reservoir elevation. However, these pressures are within the anticipated ranges and well below the identified critical uplift pressures that would threaten to cause instability problems, which is a result of the conservative design. The survey monuments show that no movement of the dam has occurred.

COST SAVINGS

Balancing cost-effectiveness with the need for a safe structure is always a challenge. However, the design/build team was able to focus on several areas and achieve cost savings without jeopardizing safety.

- The owner and contractor shared the cost liability equally on items such as foundation excavation, construction scheduling, etc. in order to remove “contingencies” or “buffers” in the construction budget that were based on unknowns. The owner and contractor worked together to keep tighter control of the construction budget and achieve cost savings.
- The owner was willing to maintain a relatively flexible working schedule to optimize construction efficiency. When cold weather limited RCC production and placement, the suspension of RCC production until warmer weather resulted in a more efficient RCC production rate and overall cost savings.
- The engineer reviewed and responded to requests for information and change orders extremely promptly (sometimes in less than an hour) to keep construction schedules on track and minimize downtime.
- The entire design/build team worked together and took equal ownership of the project. The understanding that this project was the responsibility of all involved created an atmosphere of trust. No one entity tried to take advantage of the situation; rather, the team created a mutually beneficial environment.

Figure 9. Completed dam with downstream soil cover.

The total project cost (engineering and construction) for the design and construction of the Pine Brook Dam was approximately US$4.5 million. While it is difficult to compare these costs to those of similar projects, these costs are significantly lower than the estimates discussed during the proposal phase. It is believed this process saved between US$3 million and US$4 million as compared to the more traditional design-bid-build process.

We can make this claim by comparing the Pine Brook Dam with the Genesee Dam, which was completed one year after the Pine Brook Dam and shared many of the same design characteristics. The following table compares these two projects.

Table 2. Comparison of Pine Brook Dam with Genesee Dam

	Pine Brook Dam	**Genesee Dam**
Year Completed	2006	2007
Engineer-of-Record	Del Shannon	Steve Jamieson
Contractor	ASI Constructors	ASI Constructors
RCC Volume	34,140 yd^3 (26,150m^3)	34,300 yd^3 (26,280m^3)
Conventional Concrete Volume	4,300 yd^3 (3,290m^3)	2,900 yd^3 (2,220m^3)
Reservoir Volume	101 acre-feet (124,600m^3)	101 acre-feet (124,600m^3)
Principal Spillway Capacity	500 cfs (14.2m^3/s)	550 cfs (15.6m^3/s)
Emergency Spillway Capacity	4,100 cfs (116m^3/s)	4,200 cfs (119m^3/s)
Upstream facing	Conventional concrete	Conventional concrete
Downstream facing	Unformed RCC with soil cover	Unformed RCC with soil cover
Engineering Cost	US$450,000	US$990,000
Final Construction Cost	US$4.0 million	US$7.3 million
Total	**US$4.5 million**	**US$8.3 million**

The Genesee Dam was originally conceived as a traditional design-bid-build project, but the low bid for the project ($12.5 million) was over twice the cost of the engineers estimate. By altering the design and incorporating many of the lessons learned from the Pine Brook Dam the total construction costs of the Genesee Dam project were lowered by nearly half to $7.3 million.

CONCLUSIONS

Under the right circumstances, the design/build approach can offer significant cost and schedule advantages. We believe that successful implementation of the design/build approach for a dam project begins with a committed team and includes:

- An educated owner who is willing to take calculated risks, become involved in the process early, and continue to provide input and direction where required
- A contractor with expertise in the design and construction practices required who is also creative and understands the design and construction issues associated with dams
- A competent, decisive and resolute engineer who not only involves the owner and contractor in the design process but also welcomes their input when design challenges are identified
- A permitting staff that remains involved through the design process and allows for creative solutions to conventional and unconventional designs

ACKNOWLEDGEMENTS

The Pine Brook Water District is grateful to ASI Constructors and Del Shannon as the Engineer of Record. Thanks to the hard work and cooperation of everyone involved in this project not only did the District end up with a high quality dam, but one of the, if not the most, cost effective dam of its size. After three years of operation this project has exceeded the District's expectations and remains a source of pride for the community. Picking the right "team" with the proper experience and expertise is a large part of what made this project what it is today.