Replacement of a Deteriorated Earthfill Dam with an RCC Gravity Dam

The Penn Forest Dam Replacement Project

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REPLACEMENT OF A DETERIORATED EARTHFILL DAM WITH AN RCC GRAVITY DAM

THE PENN FOREST DAM REPLACEMENT PROJECT

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ABSTRACT

Penn Forest Dam is a large earthfill embankment dam that impounds one of the City of Bethlehem's two major water supply reservoirs. The embankment dam was 145 feet high and 1,930 feet long, and was constructed between 1956 and 1958. On May 18, 1960, during the first filling of the reservoir, with the water level about 4.5 feet below normal pool, a large sinkhole developed on the upstream embankment slope. The reservoir was immediately lowered and various repairs performed. During the period 1964 to 1994, the reservoir was operated under the scrutiny of a continuous and extensive instrumentation monitoring program. In July 1994, with the reservoir level at normal pool, piezometer readings in the foundation rock in the vicinity of the former sinkhole area declined abruptly indicating a potential dam failure. Emergency response procedures were initiated and an extensive investigation was performed to evaluate the condition of the dam and develop alternative remediation measures. Replacing the earth embankment with an RCC dam at a total project cost of approximately $65 million was the selected remedial alternative.

This paper discusses the deficiencies in the earth embankment which led to the replacement of the dam, and describes several innovative design features of the new RCC dam. Key design features discussed include: (1) construction of the steep (0.5H:1V) downstream RCC face, (2) the improved method of attaching a PVC liner to the upstream precast panel facing system, (3) the computerized monitoring and control system used to grout the foundation, and (4) the accelerated construction of the dam which required eleven separate contracts.

The new 180-foot high and 2,050-foot long RCC dam was completed in December 1998. The new dam required approximately 380,000 cubic yards of RCC to construct, and is the third largest RCC dam in the United States.

BACKGROUND

FIRST INCIDENT DURING INITIAL FILLING - 1960

Problems plagued the earthfill dam from the beginning. In April 1960, during first impounding, approximately 350 gpm of turbid seepage emerged from a road cut immediately downstream of the dam and, a month later, a sinkhole developed on the upstream slope of the embankment near the right abutment. The sinkhole, which was reported to be on the order of 15 feet in diameter and more than 15 feet deep, raised the

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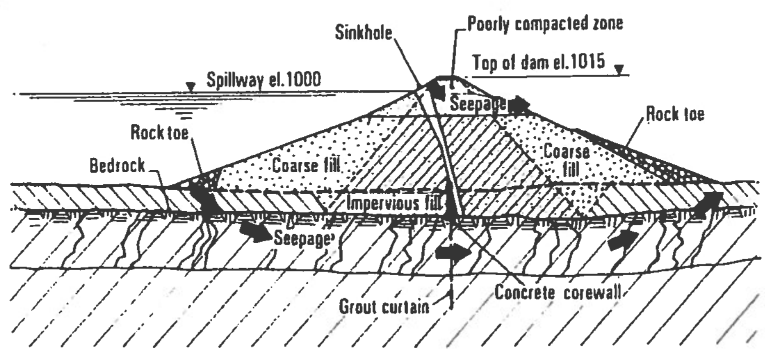
alarm, resulting in a series of emergency steps to prevent catastrophic failure of the dam. Approximately 100 cubic yards of silt and shale fragments were initially dumped in the sinkhole. The fill placement had no measurable effect on the leakage, and the reservoir was subsequently lowered about 26 feet below spillway crest. Measurable seepage was reduced to approximately 90 gpm at that pool level.

Sinkhole, May 1960

Initial Repairs, May/June 1960

Initial repairs consisted of grouting the underlying foundation rock in the vicinity of the sinkhole and pressure injecting surface-hydrated bentonite lumps and cellophane strips in the embankment to fill the voids. During drilling for grouting, voids were encountered in the embankment up to 18 inches in diameter. The foundation rock was grouted with cement grout mixed in a ratio of 1:1 by volume. The grouting program did not significantly reduce the measurable seepage emerging from the embankment.

Further investigations were performed and additional professional opinions from several engineering consultants were sought to determine the next course of action. At this point Gannett Fleming became involved in the project. There was general concurrence that the failure mechanism was piping of the embankment materials into the fractured rock foundation. Numerous concerns were expressed regarding the original design, construction, and emergency repairs. As a precautionary measure, Gannett Fleming recommended that a controlled filling program be used to further evaluate the conditions in the dam, with the results to be used as a basis for determining the need for additional repairs. A controlled filling program was implemented in 1964 after installation of numerous embankment and foundation instruments consisting of 275 piezometers, several weirs to monitor seepage, and a network of survey monuments on the embankment. The reservoir first reached spillway crest elevation on October 3, 1969, almost 10 years after the dam was first constructed. Throughout the 5-year filling period there were indications of changes in seepage conditions, but none which were deemed



Embankment Section With Sinkhole

to be of such magnitude as to require additional repairs. Total measurable seepage downstream of the dam with the reservoir elevation at spillway crest was approximately 450 gpm.

DAM INSTRUMENTATION AND MONITORING - 1969 to 1995

Through the 26-year period from 1969 to 1995, the embankment dam was aggressively monitored. Summary reports assessing the condition of the dam were prepared in 1975 and 1983. In both reports, ongoing changes in piezometric levels were reported along with high but stable seepage flow rates. Throughout the 26-year period, the scope of the monitoring program was scaled back. Near the end of this period the monitoring program consisted of reading approximately 184 instruments on a biweekly basis, including five seepage weirs and two seepage flumes. Data for 49 of the instruments judged to be key indicators of the dam's performance were regularly plotted and reviewed for changes and long term trends.

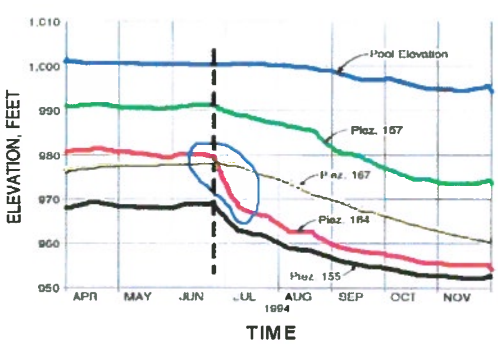
Monitoring Seepage

Through that same period, the following other activities occurred in connection with the Penn Forest Dam:

- Phase I Inspection under the National Dam Inspection Program in 1978;
- Construction of an inverted filter over a concentrated seepage discharge point at the toe of the dam in 1982;
- Performing stability analyses for the downstream slope of the embankment in 1986;
- Constructing a toe drain system in the right abutment area and blanket drains on seepage areas on the downstream slope of the dam; and
- Annual inspections of the dam and appurtenant features.

1994 INCIDENT AND EMERGENCY RESPONSE

In July 1994, while the pool level was being maintained at spillway crest, piezometric levels in instruments located in the foundation rock in the sinkhole area began to decline. The decline was masked for a period of time because drawdown of the reservoir started at approximately the same time. The pool level dropped approximately 5 feet and remained at that level for several months. Records show that piezometric levels in the foundation rock continued to gradually decline during that period. By November 1994, plotted piezometric records showed a sufficient decline in seven instruments to warrant implementing precautionary measures.



Piezometer Readings Signal Problem

Overall, piezometric levels in the foundation rock in the vicinity of the original sinkhole declined approximately 10 to 20 feet in the 5 month interval from July to November. The changes in the piezometric levels were interpreted as a possible early warning sign of recurrence of piping. Subsequently, it was determined that a total of 15 instruments in the general vicinity of the sinkhole area were affected to varying degrees. A review of the seepage records showed that the total seepage increased to over 900 gpm which further indicated that the dam was deteriorating.

In response to the observed conditions and the overall history of Penn Forest Dam, the City of Bethlehem implemented a series of emergency response measures recommended by Gannett Fleming. The emergency response measures, summarized below, remained in effect until January 1995, at which time the pool had been drawn down to approximately Elevation 975, 25 feet below spillway crest. Following the emergency measures, the reservoir was further drawn down and held at Elevation 950 during subsequent investigations.

Penn Forest Reservoir at Elevation 950

Emergency Response Measures

- Notified the Corps of Engineers, the State DEP Division of Dam Safety, and the County EMA personnel of conditions at the dam.
- Began drawdown of the reservoir 2 feet per day until the pool level reached Elev. 985, then at a reduced rate to Elev. 950.
- Maintained 24-hour visual surveillance of the dam.
- Read and plotted readings from selected piezometers and all seepage weirs daily.
- Stockpiled emergency supplies of geotextile and fill material at the damsite.
- Performed weekly detailed inspection of the dam including surveying embankment monuments.

INVESTIGATIONS AND CONCLUSIONS

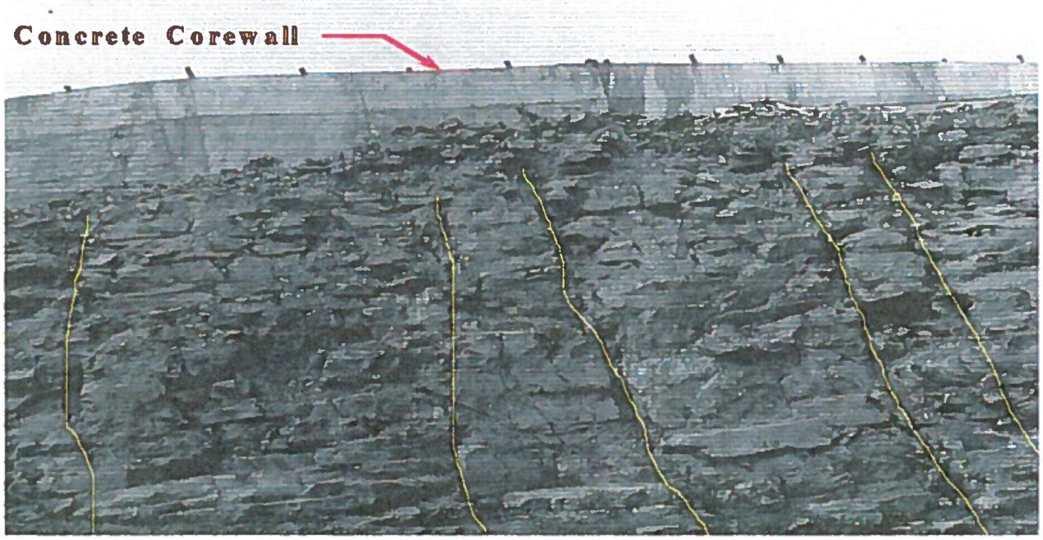
Gannett Fleming was subsequently authorized by the City to perform detailed investigations to evaluate the condition of the dam and identify repair alternatives. As the extent of the problems with the embankment and foundation became better known, and it was recognized that repairs would be costly, it was recommended that the City seek a second opinion and appoint an independent Board of Consultants (BOC) to review Gannett Fleming's investigations. The BOC was comprised of recognized dam engineering experts, including Joe Ellam of the Pennsylvania DEP, James Gould of Mueser Rutledge, Steve Tatro and Arthur Waltz of the U.S. Army Corps of Engineers, and Richard Kramer formerly with the U.S. Bureau of Reclamation.

The detailed investigations of the dam confirmed that the original sinkhole failure at Penn Forest Dam had been caused by a combination of design and construction defects, and that the repairs carried out in 1960 had been low-cost, high-risk methods which would not be appropriate today. Consequently, the defects which had caused the initial failure were still present, and represented high long-terms risks. Furthermore, Gannett Fleming and the BOC found that the deficient zones within the dam foundation and embankment were not limited to the original sinkhole. There were clear indications of seriously deteriorating conditions, and warning signs of a developing failure. Gannett Fleming advised the City that satisfactory long-term performance of the dam could not be expected without major repairs to the entire dam. The most fundamental requirement was to essentially eliminate seepage through the embankment and foundation.

The original sinkhole failure was caused by a combination of design and construction defects that led to massive seepage and erosion of material from within the embankment. Failure was initiated by flow into the foundation from the reservoir area and through cracks in the embankment entering open rock fractures. The dam had no design features to prevent erosion from progressing to the point of failure. The detailed investigations identified the following primary defects in the dam:

PRIMARY DESIGN DEFECTS:

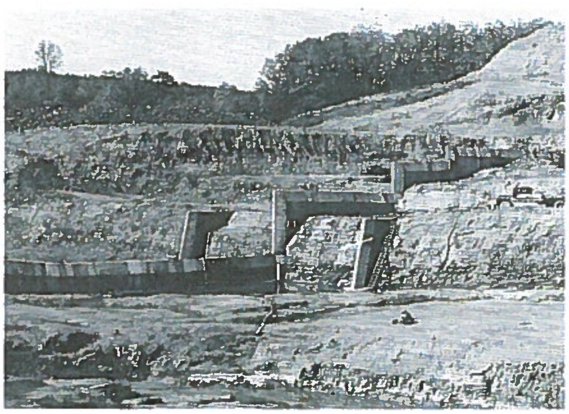
- ***The Original Foundation Grouting Program Was Ineffective***. Grout holes were vertical and did not intersect the principal joint sets which are near-vertical. One set is orientated in an upstream and downstream direction and the other is parallel to the dam axis. The grout curtain was a single line design which is inadequate for a dam of this size and with these foundation conditions. In addition, the frequent use of sand in the grout mix limited the penetration of the grout in large fractures.
- ***The Dam Was Constructed Without Internal Filter Drains***. Without internal filter drains, there was no mechanism to prevent piping from progressing after it began. Further, the drains that were constructed were not compatible with the rolled coarse fill or the underlying foundation soils, and had the potential to promote piping rather than prevent it.



Construction Photo of Concrete Core Wall on Fractured Rock Foundation

PRIMARY CONSTRUCTION DEFECTS:

- ***The Abutments of the Dam Were Not Adequately Prepared***. The rock foundation at the dam abutments had three to five near-vertical ledges or steps. At least one of these steps was over 25 feet high. Rather than trimming the rock ledges to a uniform slope, multiple concrete cutoff fins or walls were constructed at the vertical steps. Steps in the abutments can result in the formation of a soil arch and differential settlement. Both of these results made the embankment more susceptible to cracking.
- ***The Dam Foundation Was Not Adequately Prepared***. At the east abutment the corewall sits on a thin ridge of highly fractured rock which should have been removed to a substantially greater depth than what was performed.
- ***Poor Quality Control During Construction***. Subsequent excavation of the embankment found roots, oversized material, and large tree limbs and stumps in the fill. Compaction along steep abutment ledges and along the corewall is also suspect. Construction photographs show that these areas were likely compacted with small hand equipment without reducing lift thickness, which resulted in minimal compaction. In addition, the top 45 feet of the embankment was found to be only 90 percent of maximum dry density.



Vertical Steps At Abutments

Inadequate Compaction of Fill Material

REPAIR OPTIONS AND SELECTED ALTERNATIVE

REPAIR OPTIONS

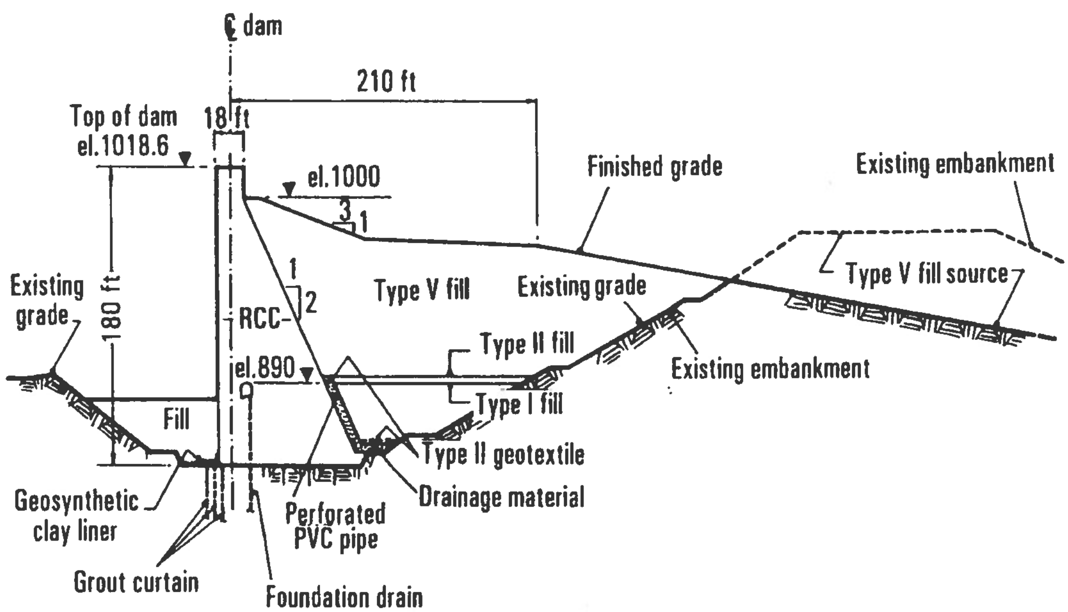
Seven options were considered for repairing, replacing, or removing the dam from service.

Option 1: Grout the embankment and foundation using a variety of techniques
Option 2: Partially remove and reconstruct the dam
Option 3: Install an impervious blanket or liner on the upstream slope of the dam and a cutoff at the upstream toe of the dam
Option 4: Install a concrete diaphragm wall through the center of the dam and into the foundation
Option 5: Remove the existing dam and replace with a new structure
Option 6: Breach the existing dam and develop a new source of water supply
Option 7: Lower the existing dam and create a lower permanent pool. This would also require developing a new supplemental source of water supply

Based on an evaluation of the conditions at the dam, several of the aforementioned options were considered impractical, and three options emerged for final consideration. The repair options selected for further consideration included Options 3, 4, and 5.

SELECTED OPTION

Option 5 - remove the existing dam and replace with a new structure was chosen by the City. This option consisted of constructing a roller-compacted concrete (RCC) gravity dam approximately 460 feet upstream of the existing embankment dam. The alignment of the RCC dam is such that it allows continued use of the existing spillway and outlet works. The RCC gravity dam is buttressed on the downstream face by earth fill from the existing embankment. Advantages associated with this option included: (1) it restored Penn Forest Dam to its original operating level, (2) the proposed RCC gravity section relied on the existing embankment only for minimal support and a minor failure of the embankment, even though highly unlikely, would not have a significant impact on the overall performance of the new dam, and (3) it had the longest service life with minimal maintenance and risk of failure. The alignment and location of the RCC dam resulted in savings of about $20 million compared with a new stand-alone dam, since the intake tower and outlet works conduit was recycled, and road relocation and environmental impacts associated with a new dam site downstream of the existing site were avoided.



Typical Section of RCC Replacement Dam

INNOVATIVE DESIGN FEATURES

BUTTRESSING THE DOWNSTREAM RCC FACE WITH EARTHFILL

The downstream face of the dam was formed by concurrent placement of RCC and the earthfill embankment. This allowed the downstream slope of the dam to be steepened from 0.8H:1V to 0.5H:1V, thereby reducing the volume of RCC. The buttressing effect of the embankment fill enhances the stability of the reduced cross section. RCC waste or overbuild was minimized by placing the downstream end of the RCC lift against a temporary 1-foot high form before placing the downstream fill. In addition to providing a form for the RCC, the soil fill covering the downstream face of the RCC protects the untreated RCC face from weathering, provides a thermal blanket to reduce cracking from thermally induced stresses, and increases the sliding and overturning stability of the dam.

Temporary Forms for RCC

RCC Placed Concurrently With Fill.

Overview of New RCC Dam With Regraded Embankment Against Downstream Face of the Dam

THE UPSTREAM PRECAST PANEL FACING SYSTEM

Willow Creek Dam was the first RCC dam constructed in the United States and used this system to form the upstream face. This upstream facing method provided an innovative means of forming the upstream face with an economical stay-in-place form which is both durable and aesthetically pleasing. Although Willow Creek Dam was designed to be stable with full uplift along each joint, the seepage which emerged from the lift joints at the downstream face of the dam during filling of the reservoir was found to be undesirable.

Since Willow Creek, this method was modified by adding an impervious liner to the unexposed face of the precast panel to provide a watertight barrier. In most cases the liner material is a 65-80 mil PVC material, however, LDPE liner material was used at Christian E. Siegrist Dam. The first five dams in the U.S. to use this method; Winchester Dam, Christian E. Siegrist Dam, Spring Hollow Dam, Hudson River # 11 Dam and Big Haynes Dam, relied on a "T-Lock" surface anchor system to attach the sheets of liner material to the back of the panels. Except for Big Haynes, these dams used the common panel size of 4 feet high, 16 feet long and 4-inches thick.

At Penn Forest Dam, an improved method of attaching the sheets of liner material was developed. The PVC liner material (Sibelon CNT 2800) was manufactured by CARPI of Italy, and consists of an 80 mil high performance PVC coupled with a $200 g/m^2$ geotextile. The liner was attached to the panels by first placing the concrete mixture into the panel forms, followed by rolling and vibrating the liner material onto the exposed concrete surface of the panel with the geotextile side of the material placed on the wet concrete. The liner remains attached to the panel through the bond made between the concrete and the geotextile.

This method of attaching the PVC liner to the precast panels was initially tested for the Penn Forest project by pulling apart several panels after the PVC liner had been partially welded to adjacent panels. The destructive testing demonstrated that the stress concentrations in the PVC liner material did not concentrate at the welds between panels, but became distributed over much of the panel area. It was observed that as the panels were pulled apart, the bond between the geotextile and the PVC liner failed first, allowing the liner material to behave elastically and stretch more than 18 inches at the joints before failing. This method of liner attachment offers several benefits over the traditional "T-Lock" surface anchor system for liner attachment, including: reduced cost, greater flexibility, improved liner properties, and better resistance to stress concentrations.

Casting Precast Panels

Destructive Testing of Panel Welds

At Penn Forest Dam the first rows of panels were 4 feet high and 16 feet long. Later, the contractor exercised the contract option to increase the height of the panels to 6 feet. Using larger panels decreased the time required to place panels, and reduced the total length of heat welded horizontal and vertical joints by approximately 35 percent. On Penn Forest Dam the total panel area for the upstream face of the dam is approximately 230,000 ft^2. This method of attaching the liner to panels was subsequently used to construct Buckhorn Dam in North Carolina, and is now proposed for two new RCC dams in the United States.

Looking at Upstream Face of New RCC Dam During Construction, September 1998

USE OF ADVANCED GROUTING TECHNOLOGY

Grout curtains are critical elements in dam design and performance. They are expensive, time consuming to install, and require knowledge, care, and skill to construct properly. The grout curtain for the new Penn Forest Dam was designed using a new approach based on evaluating specific structure performance for various grout curtain configurations. The design approach is termed Quantitatively Engineered Grout Curtains (QEGC's), (Wilson et. Al., 1998). This approach requires sufficient geologic investigations and borings with full-depth water pressure testing to determine the foundation rock characteristics. After a thorough subsurface investigation was performed, detailed seepage analyses were performed using a state-of-the-art finite element computer model to simulate the foundation conditions to determine the need for grouting, the intensity of grouting required, the configuration of the grout curtain, and the location of the grout curtain. The grout curtain was optimized in terms of depth, width, and grouted zone permeability to meet the project performance requirements and the site specific geologic conditions. Ultimately, a 3-line curtain was chosen with the lines spaced at approximately 5-foot centers, with an average depth of 140 feet.

Since the Penn Forest Reservoir represents approximately 60 percent of the City's water supply storage, an accelerated design and construction schedule was imperative to avoid potential water shortages during construction. To accomplish this, the project was issued under different contracts. The accelerated schedule resulted in the foundation grouting being split into two separate contracts. The first line of the 3-Line grout curtain, identified as the A-Line, was performed within the footprint of the dam as part of the final excavation contract. Due to the short design period and other factors, the A-Line grouting contract was issued specifying conventional grouting methods (neat cement grouts, nutating disk water meters, agitator dipstick measurements, and pressure gages). All work on the A-Line was performed using the best conventional monitoring and control technology. Although data measurements, recording, and analysis were based primarily on mechanical instruments and manual methods, the execution of the work was at the highest standard consistent with the methods and equipment used.

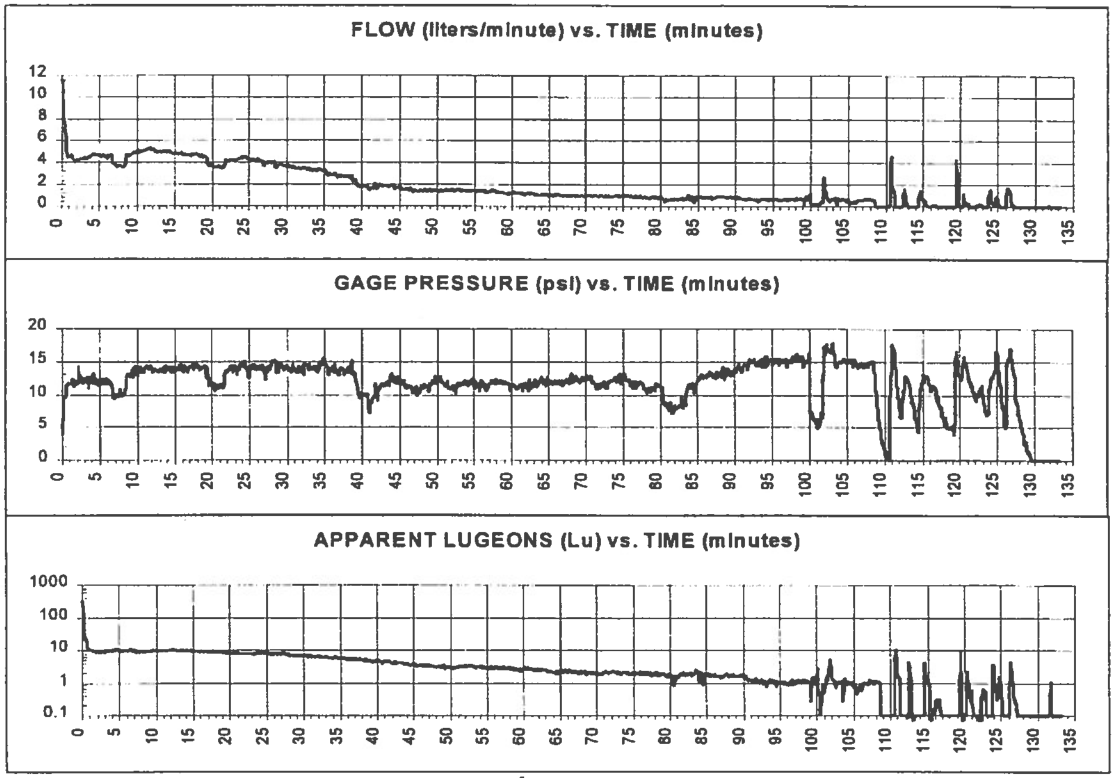
Sufficient time existed before the issuance of the second grouting subcontract for the application of advanced grouting methods. The advanced grouting method employed eight different base mixes consisting of varying concentrations of Type III cement, fly ash, bentonite, welan gum, and superplasticizer. This advanced method produced balanced, stable grouts which were formulated to provide zero bleed, low cohesion, and systematic thickening of the grout as required during the injection process. The advanced grouting was also performed using the most advanced monitoring system available in the United States. The basic components of the computer assisted grouting system included pressure transducers, magnetic flow meters, automated recorders linked to computers, and a radio communication system. This software called CAGES provides real-time graphical plots of the flow rate, pressure, and apparent lugeon value with time. The advanced grouting was performed through a plinth constructed along the upstream heel of the dam outside of the dam's footprint. This enabled the grouting of the B- and C-Lines to proceed concurrently with the construction of the RCC dam.

Grouting Through Plinth

By using both conventional and advanced grouting methods on the same project, a direct comparison can be made between both grouting methods. A comparison of both methods found, without question, that the advanced grouting method with computer assisted monitoring and control technology allowed the work to be performed in a more technically effective manner, faster, and at significantly lower cost. Specific findings are as follows:

Technical Benefits of Advanced Grouting Method:

- Real time data is obtained at 5-15 second intervals thus eliminating critical events such as pressure spikes
- Data obtained is more accurate enabling use of higher grouting pressures
- Provides detailed, permanent graphic records showing the entire time history for each operation on each stage
- Provides a more reliable grout curtain with better durability.



Typical Real-Time Data From Advanced Grouting Method

Time and Cost Benefits of Advanced Grouting Method:

- Reduced inspection manpower requirements
- Reduced total construction time approximately 10 weeks (25 Percent)
- Resulted in savings in inspection and construction costs of about $500,000

ACCELERATED CONSTRUCTION REQUIRING MULTIPLE CONTRACTS

As previously noted, Penn Forest Reservoir is the primary source of water supply for the City of Bethlehem, storing over 6.4 billion gallons of water. Since replacement of the dam required completely emptying the reservoir during construction, it was imperative that the design and construction of the dam be completed as quickly as possible. This necessitated a fast track design where construction contracts were advertised as soon as a design element was completed. Extensive planning and coordination was required to ensure minimal construction delays and availability of construction materials when needed. Construction challenges facing the design team included the following:

1. The middle 300 feet of the 900-foot long, 12-foot diameter diversion conduit was plugged with approximately 1000 cubic yards of 8000 psi concrete. The concrete plug also included sections of large cast iron pipe and other embedded metal items. Removal of the concrete plug was necessary to provide adequate diversion during construction and to provide access to the gallery of the new RCC dam after construction. Removal of the concrete plug required extensive confined space entry work and was on the critical path for other construction work.

2. Diversion of streamflows from the 16.4 square mile damsite required diversion of the streamflows in two phases. Phase 1 lasted one year from July 1996 to July 1997 until the 12-foot diversion conduit in the existing dam was put back into service. All flow during this period was diverted through a 48-inch water supply conduit located in the intake tower. A 2,000-foot long, 25-foot high cofferdam was constructed just upstream of the existing dam. The capacity of the diversion works during Phase I was approximately equivalent to the 2-year flood. The second phase began once the concrete plug was removed from the diversion conduit. Flows were then diverted through both the 12-foot conduit and the 48-inch water supply line. The capacity of the diversion works for Phase II was increased from a 2-year flood to a 25-year flood.

3. Over 850,000 tons of coarse and fine aggregate for the new RCC dam needed to be produced from an offsite source and delivered to the damsite. Production and delivery of the aggregates needed to be performed during the cooler months of the year to satisfy stockpile temperature requirements.

4. Over 250,000 square feet of precast panels needed to be fabricated and delivered to the site.

A total of 11 contracts with a total value of $50 million were issued to construct Penn Forest Dam (see table which follows). At one time during construction, the work of five different prime contractors needed to be coordinated and managed at the worksite. During the three years of construction, additional challenges were encountered including a major flood which inundated the worksite, lengthy labor union strikes, government delays in issuing legal wage rates, and two years of drought conditions which intensified the need to complete the dam ahead of schedule.

Flooding of Work Area, December 1996

Penn Forest Dam Replacement Project
Summary of Construction Contracts

ID	Contract Title	Bid Date	Low Bid	Description of Work
I	Stream Diversion Pipe	May 15, 1996	Lane Enterprise $43,036	Furnishing and delivery of 200 feet of 12-foot diameter corrugated-steel pipe.
IA	Construction of Temporary Cofferdam and Appurtenant Works	June 4, 1996	James D. Morrissey $1,027,550	Construct temporary earthfill cofferdam upstream of the existing Penn Forest Dam. The cofferdam is approximately 20 feet high and 1,400 feet long. Appurtenant works include installing approximately 160 feet of 12-foot diameter CMP and fabricating and installing a steel bulkhead for the upstream end of the 12-foot diameter conduit.
II	Diversion Conduit Modifications & Concrete Plug Removal	Aug. 23, 1996	Rencor, Inc $511,220	Remove 300 feet of concrete plug, 820 feet of 36-inch diameter cast iron pipe and appurtenant structures, and remove sediment from within the 12-foot diameter diversion conduit located in the existing Penn Forest Dam. Also, various improvements to the outlet channel.
III	Excavation and Related Work	Sept. 10, 1996	James D. Morrissey $2,766,279	Construct access roads, excavate soil and rock materials, install erosion and sedimentation facilities, dewater excavation areas, remove existing instrument casings, install and monitor instruments, cleanup excavated surfaces, and other related items.
IV	Foundation Excavation and Preparation	Feb. 28, 1997	Lane Construction $8,932,450	Excavate and stockpile rock and soil materials, clean excavated surfaces, dewater excavated areas, complete construction of 12-foot diameter conduit, divert streamflows from work areas, construct concrete plinth, drill and grout dam foundation (A-Line), and other items.
VA	RCC Dam and Appurtenant Works	Jun. 24, 1997	Conti Enterprises $23,478,392	Construct new RCC dam using 380,000 cubic yards of RCC, drill and grout foundation (B- & C-Lines), install 250,000 square feet of precast panels, place 860,000 cubic yards of earthfill, and other work.
VB	RCC Aggregate Procurement	Oct. 30, 1996	Eureka Stone Quarry $7,925,000	Produce and deliver 460,000 tons of coarse aggregate and 380,000 tons of fine aggregate.
VC	Precast Concrete Panels	May 23, 1997	New Enterprise Stone and Lime $2,392,207	Produce and deliver 250,000 square feet of precast panels and panel accessories.
VIA	Appurtenant Works Modifications	April 14, 1998	Conti Enterprises $757,757	Repair existing concrete spillway, rehabilitate access roads, replace access bridge, construct minimum release weir, and other work.
VIB	Mechanical and Electrical	May 7, 1998	Lomardo & Lipe $439,980	Furnish and install mechanical and electrical equipment for gallery tunnels with a length of 1,850 feet and for other appurtenant structures.
VIC	Appurtenant Works Modifications	Jun. 29, 1998	Ronca $823,000	Rehabilitate existing intake tower, tower valves and accessories, outlet works, and construct gallery entrance at the toe of the dam.

CONCLUSION

Dam designers need to learn from the experiences and success of other designers. This paper was prepared to provide dam engineers with a case study of a significant embankment dam which had serious design and construction deficiencies and to show how replacement of this structure was addressed using state-of-the-art design and construction methods.

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CAGES$_{tm}$ Computer Aided Grout Evaluation System, ECO Grouting Specialists, Ltd., Ontario, Canada, 1997.