SEEPAGE FAILURE, EVALUATION AND REMEDIATION OF PENN FOREST DAM

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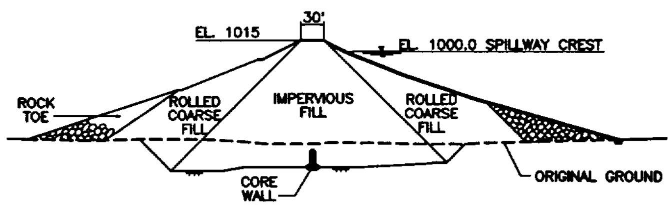
ABSTRACT

Penn Forest Dam is a large earthfill embankment dam that impounds one of the City of Bethlehem's two major water supply reservoirs. The dam is 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 spillway crest, a large sinkhole developed on the upstream embankment slope. The reservoir was immediately lowered and repairs initiated, consisting of backfilling the sinkhole with earth and rockfill and grouting of the embankment and underlying rock foundation. During the period 1969 to 1994, the reservoir was operated under the scrutiny of a continuous and extensive instrumentation and monitoring program. In July 1994, with the reservoir level at spillway crest, piezometric levels recorded by instruments in the foundation rock in the vicinity of the former sinkhole area declined rapidly, indicating a potential dam failure. Emergency response procedures were initiated and an extensive investigation was begun to evaluate the condition of the dam and develop alternative remediation measures. Studies have concluded that the recommended alternative is the construction of an RCC replacement dam at an estimated project cost of $63.3 million.

PROJECT DESCRIPTION

Penn Forest Dam is a zoned earth and rockfill embankment dam with a central impervious core and a low concrete core wall founded on rock. The dam is approximately 1930 feet long and 145 feet high. A concrete chute spillway is located in the right abutment and a concrete intake tower is located on the left abutment. Construction of the dam was completed in 1959, on Wild Creek, a tributary to the Lehigh River, in northeastern Pennsylvania. The dam is a large high-hazard structure, Pennsylvania DEP Class A-1. Penn Forest is situated just upstream of Wild Creek Dam, the other Bethlehem supply.



Typical Dam Section
Penn Forest Dam

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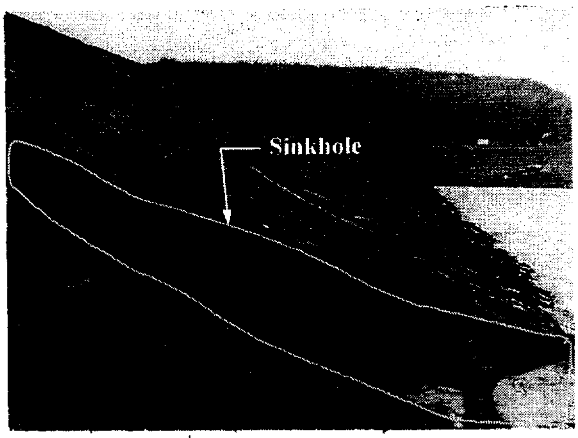
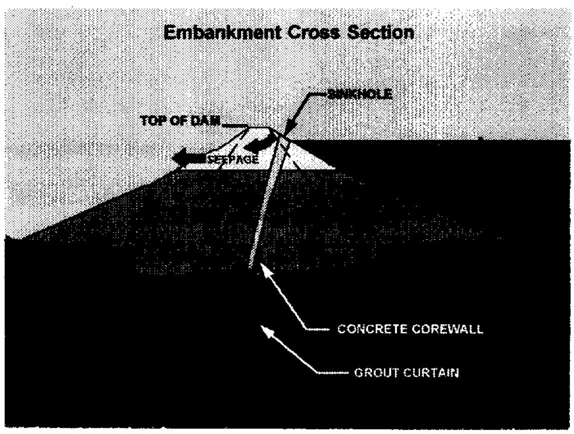
HISTORICAL PERSPECTIVE

Penn Forest Dam was filled for the first time in 1959 and 1960. On May 18, 1960, with the reservoir at Elevation 995.5 (4.5 feet below the spillway crest), a sinkhole developed on the upstream slope of the embankment. Approximately one month prior to the development of the sinkhole, seepage had been observed exiting from a road cut in the downstream area and from weep holes in the spillway stilling basin. The leakage from the road cut was turbid and reported to be approximately 350 gpm. The sinkhole, which was reported to be on the order of 15 feet in diameter and 15 feet in depth, was filled with approximately 100 cubic yards of loosely placed silt and shale fragments. The fill placement had no measurable effect on the leakage, and the reservoir was subsequently lowered to Elevation 973.6, which is 26.4 feet below the spillway crest. Seepage reduced to approximately 90 gpm at that pool level.

Repairs to Penn Forest Dam were accomplished under the direction of D'Appolonia Associates between August and October 1960. The repairs consisted of grouting the embankment and the underlying rock foundation. During drilling, voids up to 18 inches in diameter were detected in the embankment. The embankment was grouted with surface-hydrated bentonite lumps and cellophane strips, and the rock was grouted with cement grout mixed in a ratio of 1:1 by volume. Upon completion of the grouting program, seepage from the road cut area was reported to be approximately 20 gpm with the reservoir at Elevation 985.5.





Additional professional opinions were sought on the condition of Penn Forest Dam and reports were submitted in 1961 by B. K. Hough, and in 1963 by Justin and Courtney and by Gannett Fleming. There was general concurrence that the failure mechanism was piping of the embankment materials into the fractured rock foundation. The Hough and Justin and Courtney reports pointed out numerous concerns about the design, the construction, and the repairs, and both reports recommended that additional precautionary measures be undertaken. Gannett Fleming recommended that a controlled filling program be used to further evaluate the conditions in Penn Forest 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 an extensive embankment and foundation instrumentation program. Water first reached the spillway crest level on October 3, 1969. Throughout the 5-year filling period there were indications of changes in seepage conditions, but none which prevented completion of the filling or which were deemed to be of such magnitude as to require additional repairs.

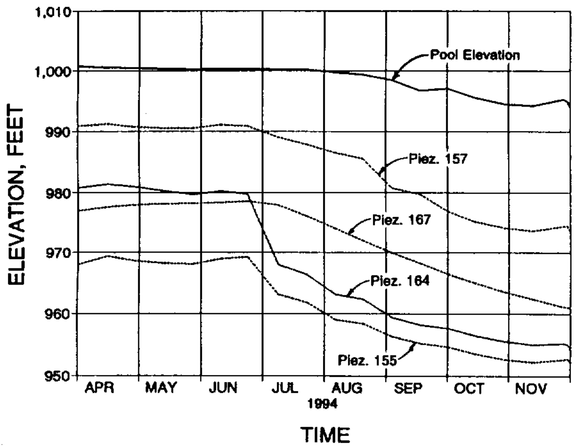
DAM INSTRUMENTATION AND MONITORING

Through the period of 1969 to 1995, a period of 26 years, monitoring of embankment and foundation instrumentation has continued. Summary reports assessing the condition of Penn Forest 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. In recent history, the monitoring program includes reading approximately 184 instruments on a biweekly basis, including 5 seepage weirs and 2 seepage flumes, but only plotting the data for a group of 49 instruments, weirs and flumes, that were considered to be key indicator instruments.

Through that same period, other activities that occurred in connection with Penn Forest Dam include the following: Phase I Inspection under the National Dam Inspection Program in 1978; constructing an inverted filter over a concentrated seepage discharge point at the toe of the dam in 1982; performing a stability analysis 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 a drawdown of the reservoir started at approximately the same time. The pool level dropped to about Elevation 995 and was 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 7 instruments to warrant implementing precautionary measures. Overall, piezometric levels in the foundation rock in the vicinity of the original sinkhole declined approximately 10 to 20 feet in the interval from July through November. The changes in the piezometric levels were interpreted as a possible early warning sign of recurrence of piping. Subsequently, it was been determined that a total of approximately 15 instruments in the general vicinity of the sinkhole area were affected to varying degrees. The additional 8 instruments that were identified as being affected include those for which data plots were not initially available and those for which the declines are detectable but substantially smaller in magnitude.



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 level had been drawn down to approximately Elevation 975. Following the emergency measures, the reservoir was further drawn down and held at Elevation 950 during subsequent investigations.

- Penn Forest drawdown at 2 feet/day until pool level reaches Elevation 985
- Maximum achievable drawdown of Penn Forest if turbid flows, whirlpools, or major new seepage develops
- Wild Creek drawdown at achievable rates until 4 feet below spillway crest
- 24-hour visual surveillance of Penn Forest Dam
- Daily piezometer readings of 16 instruments in vicinity of original sinkhole area
- Daily weir readings
- Daily plotting of piezometer and weir data
- Bi-weekly readings of other piezometers
- Stockpiling of emergency supplies (geotextile and fill material) at damsite
- Setting and weekly monitoring of Elevation survey points on Embankment
- Notification of Corps of Engineers of conditions at the dam
- Notification of County Emergency Management personnel of conditions at the dam
- Implementation of other applicable provisions of the Emergency Action Plan
- Initiation of preliminary analysis of data and possible implications
- Designation of official spokesperson

INVESTIGATIONS AND CONCLUSIONS

The engineering investigations of the foundation and embankment have been performed by Gannett Fleming, Inc., and reviewed by a Board of Consultants (BOC) comprised of recognized dam engineering experts, independently engaged by the City of Bethlehem.

Conclusions reached during the engineering investigations were documented in a report prepared for the Board of Consultants, titled: "*Study Findings and Conclusions - Penn Forest Dam*". An abbreviated summary of these conclusions is as follows:

- The original sinkhole failure at Penn Forest Dam was caused by a combination of design and construction defects that led to massive seepage and erosion of material from within the embankment.

- The repairs that were performed at Penn Forest Dam in 1960 were low cost, high risk repairs that are not considered reasonable in terms of current engineering practice.

- The defects that caused the initial failure are still present and represent high long-term risk to Penn Forest Dam.

- Instrument data shows that conditions at Penn Forest Dam have changed both in magnitude and location over the life of the dam. Deficient zones within the foundation and embankment are not limited to the original sinkhole area. The observed trends in performance are interpreted as clear indications of seriously deteriorating conditions within the dam and foundation and warning signs of a developing dam failure.

- Satisfactory long-term performance of Penn Forest Dam cannot be expected without major repairs to the dam. The most fundamental requirement is that seepage through the embankment and foundation must be essentially eliminated. Repairs cannot be limited to the sinkhole area, but must address the entire structure.

EVALUATION OF REMEDIATION OPTIONS

A total of nine options were considered for repairing, replacing, or removing the dam from service. These options are listed as follows:

- Grouting of the embankment and foundation of the dam using a variety of techniques.

- Partial removal and reconstruction of the dam.

- Installation of an impervious blanket and cutoff at the upstream toe of the dam.

- Installation of a concrete diaphragm wall through the center of the dam and extending into the rock foundation.

- Removal of the existing dam and replacement with a new structure.

- Installation of a liner on the upstream embankment slope and a cutoff in rock at the upstream toe of the embankment.

- Removal of the existing dam and development of a new source of supply.

- Partial removal of the existing dam (lowered permanent pool) and development of a new source of supply.

- Removal of the existing dam and raising of the pool level at Wild Creek Dam.

Based on an evaluation of the conditions at Penn Forest Dam, several of those options, or parts thereof, were not considered practical. The three options that merited final consideration were:

- **Option 1 - Concrete Cutoff Wall Through Center of Dam**

Description: This option would restore Penn Forest Dam to its normal operating condition. The major work elements of this option would consist of excavating the entire length of dam to Elevation 970, performing compaction grouting in known and suspected damaged areas of the embankment, installing a thin, continuous concrete cutoff wall through the dam and into the foundation rock, special treatments at the conduit and tunnel to tie the wall to these structures, and reconstructing the top of dam. A brief description of each of these work elements follows:

- Excavation of Top of Dam: Excavation of the top of dam to Elevation 970 is planned for two reasons. First, it is necessary to provide a broad working platform for the equipment used to install a cutoff wall, and second it allows removal and replacement of the upper 45 feet of the dam that was not properly compacted during original construction. The core material, random shell material, and the riprap on the upstream face would be selectively excavated and stockpiled so that these materials can be used in reconstructing the top of dam.

- Compaction Grouting: Compaction grouting is planned in known and suspected damaged embankment areas including the sinkhole area, the vicinity of the west abutment foundation ledges, and on the east abutment. Compaction grout holes would be drilled or driven to the top of rock with low mobility (compaction) grout injected in 5- to 10-foot stages as the casing is withdrawn. Compaction grouting is required in these areas to remediate cracks or voids within the embankment prior to excavating the cutoff wall trench.

- Cutoff Wall Construction: A concrete cutoff wall could be installed through the dam and into foundation rock using one of three different techniques. Each of these methods are essentially proprietary systems. These methods include using a rock mill to excavate rectangular panel holes through the earth embankment and rock under a head of bentonite slurry that is used to support the trench sidewalls in the embankment. Each panel is then backfilled with concrete, and successive panels are overlapped to make a continuous cutoff. A second method of installing a concrete cutoff is to install overlapping concrete piles called secant piles. In this method, the wall is constructed by constructing 34-inch-diameter piles to the desired depth at a primary spacing of approximately 22 inches center-to-center. After these primary piles have been backfilled with concrete and cured, secondary 34-inch-diameter piles are installed midway between the primary piles to form a continuous cutoff. A third possible method consists of constructing a wall of 24-inch nominal thickness which consists of round primary elements connected by panel-type secondary elements. The round primary elements are installed by a combination of clamshell excavation in earthfill and rotary drilling in rock. Steel casing is used to maintain an open hole in the embankment materials. The secondary elements are installed by excavating a trench between the primary elements under a head of bentonite slurry using a clamshell and rock chisels. In all of these schemes, the holes or panels are backfilled with conventional or plastic concrete by the tremie method to displace the slurry and form a continuous concrete element. All three methods have the potential to provide comparable performance at similar schedules and costs.

- Reconstruction of Top of Dam: After construction of the cutoff wall is complete the top of dam would be reconstructed using the previously excavated material to the fullest extent possible. The replacement section would be a zoned embankment containing a filter and drain. The top of dam will be raised to Elevation 1018.0 in this option to contain the PMF.

Preliminary details for this option are shown on Figure E.

Advantages and Disadvantages: The major advantages of this option are: (1) this option restores Penn Forest Dam to its normal operating level and provides additional freeboard to contain the PMF, (2) a partial, although minimal, pool may be maintained in Penn Forest Dam so long as difficulty with large slurry losses and hydrofracturing of the embankment are not experienced during excavation for the cutoff wall, and (3) a cofferdam would not be required to implement this option.

Two major disadvantages of this option are: (1) case history documents indicate that cutoff walls constructed through embankment dams have resulted in large slurry losses and additional damage to the embankments due to hydrofracturing. Large change orders and construction delays are common due to the need for additional grouting to address the slurry losses and/or hydrofracturing; and (2) the cutoff constructed under this option is not accessible for post-construction inspection. Repairs, however, could be made by grouting if defects could be located. Further, drainage downstream of the cutoff wall, to collect seepage through the wall, cannot be provided. Cutoff wall defects would be concealed and might be difficult to locate and repair.

- **Option 2 - Embankment Liner and Foundation Cutoff**

Description: This option consists of restoring Penn Forest Dam to its normal operating condition by installing a liner system on the upstream slope of the dam and a cutoff into the foundation rock at the upstream toe of the dam. The liner system and cutoff would be interconnected at a drainage gallery at the upstream toe of the dam. Other major elements of this option include excavation and backfill of the sinkhole area, compaction grouting in known and suspected damaged areas of the embankment, special treatment at the tunnel to tie this structure to the cutoff, and installation of a cofferdam and associated diversion works. Option 2 is shown on Figure F. A brief description of each of the major work elements follows:

- Liner System: Four liner materials were considered for installation on the upstream slope: steel, concrete, hydraulic asphalt, and synthetic materials. Steel is the highest cost liner option and, for that reason, was quickly eliminated from consideration. A brief description of the other three materials is as follows:

Cross Section of Option 1

Concrete Cutoff Wall Through Dam

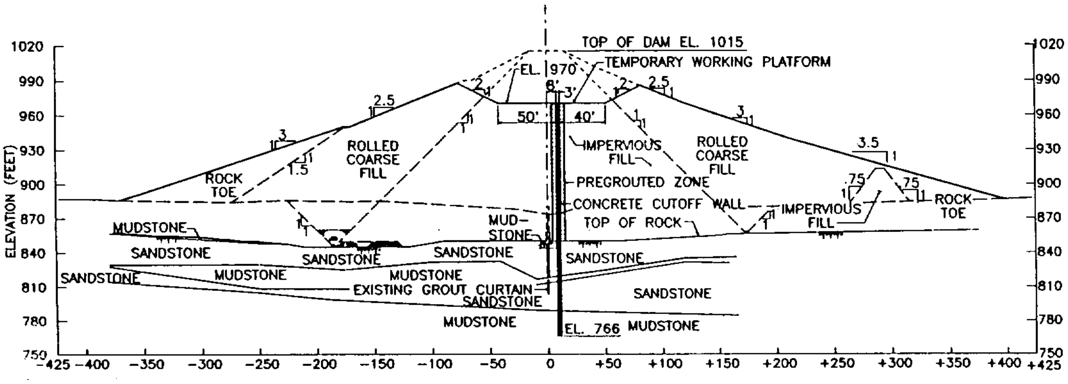


Figure E

Cross Section of Option 2

Liner with Grout Curtain

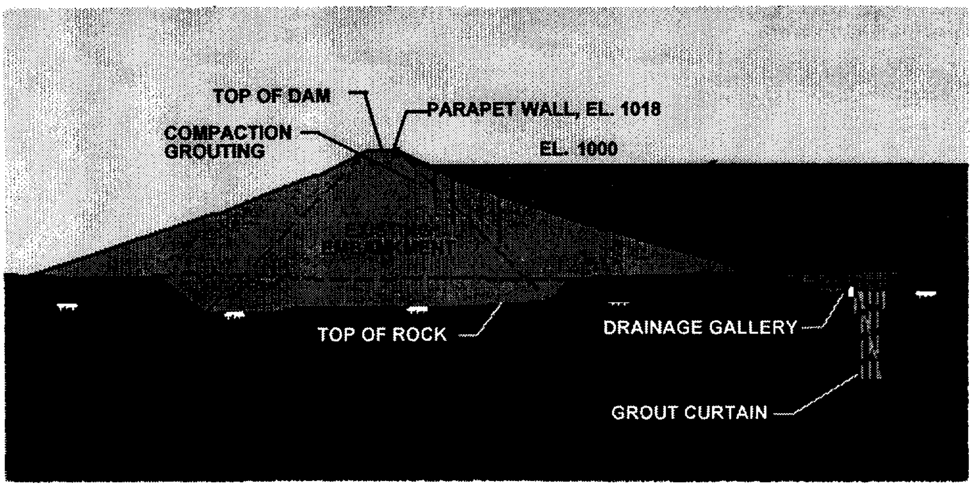


Figure F

- Hydraulic Asphalt: Although hydraulic asphalt has been used for lining dams and reservoirs for about 60 years, recent use of asphalt on dams in the United States has been limited. The technology of hydraulic asphalt for dam construction, however, is well developed but has been utilized more frequently in California and overseas. The materials are suitable for use with potable water supplies. The equipment and materials required for this type of construction are not unusually specialized, however, procedures for paving on a relatively steep slope are not commonly practiced by local contractors. Suitable construction equipment and an experienced labor force for installing an asphalt liner on a dam slope may be limited in the Eastern United States. Hydraulic asphalt has sufficient impermeability to essentially eliminate seepage through the embankment. Asphalt also exhibits some flexibility, allowing it to tolerate minor movements of the embankment that commonly occur during normal filling cycles.

- Concrete: Concrete is the most common material used for lining the upstream slope of embankment dams. Although it has been used on numerous dams in the United States in the past, its use at the current time is limited. However, the technology is well developed and installation of concrete linings does not require unusually specialized equipment or labor force. The main disadvantage of concrete is its brittleness. The permeability of concrete is sufficiently low to essentially eliminate seepage through the embankment although some minor, but acceptable, leakage would occur through minor cracks and defects in the waterstopped joints.

- Synthetic Liner: Use of synthetic liners on embankment dams has been relatively limited. However, synthetic liners have been used extensively on concrete dams and landfills in the past 10 years, thereby advancing the technology of this class of materials. The impermeability and flexibility of this type of material is excellent, provided it is installed correctly. However, the material is fairly fragile and could be subject to damage during installation. In contrast to asphalt and concrete, a synthetic liner must be covered with protective layers of earth and rock materials and, therefore, would not be accessible for routine inspection or repair.

Of the three materials, the synthetic liner and hydraulic asphalt are believed to have the lowest cost. Concrete is estimated to have the highest cost. Regardless of the type of material selected for the liner system, a drainage system should be installed between the liner and embankment to collect any seepage through the liner and from surface infiltration and groundwater entering behind the liner from the abutments and embankment. Seepage from the drainage system would be routed to a drainage gallery constructed in the foundation rock at the upstream toe of the dam. The drainage gallery would also be used to collect seepage in the foundation rock intercepted in drilled drain holes located downstream from the foundation cutoff.

Foundation Cutoff: Several methods are available for constructing the cutoff in the rock foundation at the upstream toe of the dam. Two options have been investigated for

Penn Forest Dam: a conventional grout curtain and a concrete cutoff wall. The cutoff wall could be constructed with any of the methods described in Option 1.

- Compaction Grouting: Compaction grouting similar to that described for Option 1 would also be used for this option. The purpose of the grouting would be to strengthen weak areas in the embankment so that sufficient support is provided for the liner system.

Advantages and Disadvantages: The major advantages are: (1) this option restores Penn Forest Dam to its normal operating level, (2) the design incorporates drains downstream of the liner and cutoff systems to safely collect and monitor seepage bypassing these systems, and (3) both the liner and cutoff systems are accessible for inspection and repair, if needed. The primary disadvantage of this option is the reservoir would be completely lowered during construction. A cofferdam located upstream of the work area, however, would permit stream flows into the reservoir to be released through the 48-inch conduit into Wild Creek with minimal contamination. A second disadvantage is that the liner system relies on the existing embankment for its support. The investigations conducted to date have revealed the presence of voids and soft materials within the dam. All of these deficiencies may not be detected and repaired by the proposed compaction grouting. As a result, remedial repairs of the liner and/or cutoff may be required in the future to assure successful performance of the dam.

- **Option 3 - Roller-Compacted Concrete Replacement Dam**

Description: This option consists of constructing a roller-compacted concrete (RCC) gravity dam approximately 460 feet upstream of the centerline of the existing earth embankment dam. The alignment of the RCC gravity dam is such that it can make full use of the existing spillway and outlet works. This option is shown on Figure G. The major components of this option are as follows:

- RCC Gravity Dam: The RCC gravity dam will be buttressed on the downstream face by earth material from the existing embankment. The earthfill buttress allows the base width of the gravity section to be slightly reduced in comparison to the base width for a concrete gravity dam. This reduction in section reduces the quantities required for foundation excavation and preparation and for roller-compacted concrete.

  The gravity dam would be founded on firm rock. A conventional grout curtain penetrating through the foundation rock will serve to reduce potential for underseepage. A synthetic liner embedded in precast panels on the upstream face of the structure would serve to prevent seepage through the structure. Drains would be provided for both the foundation and the dam to control and monitor seepage and uplift pressures acting on the base of the dam. Drains would also be effective in controlling pore pressures between RCC lift layers.

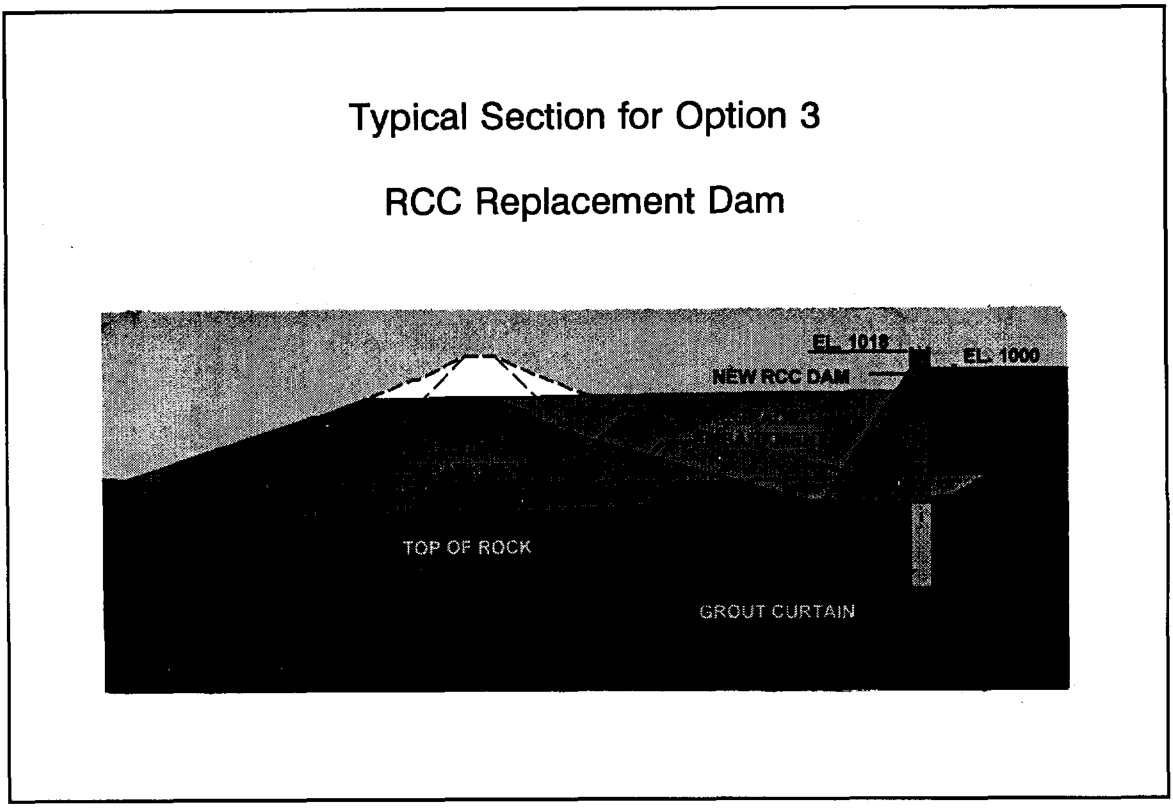


Figure G

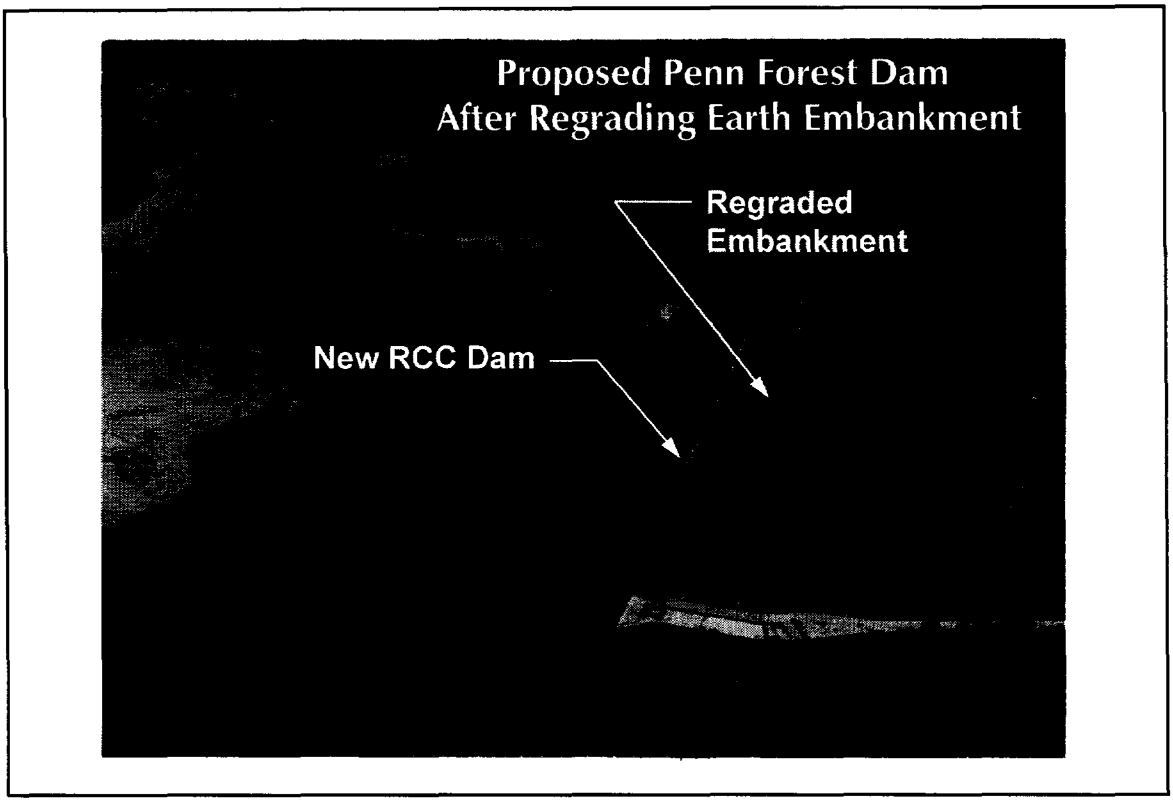


Figure H

The drains would be connected to a drainage gallery located near the base of the structure. Any seepage collected in the drainage gallery could be discharged to the existing concrete diversion conduit. The drainage gallery also provides access to the foundation of the dam should any remedial foundation grouting become necessary during the life of the dam.

- Existing Appurtenances: The RCC gravity dam is positioned upstream of the existing embankment in order to replace the embankment while still making use of the existing appurtenances. The existing spillway and outlet works would remain in service for this option. The existing spillway approach walls would be raised 3 feet to increase the spillway capacity to the PMF. The existing 12-foot-diameter concrete diversion conduit would be modified to maintain its service as a low-level outlet for the reservoir. Only minor repairs are planned for the existing intake tower.

- Stream Diversion During Construction: Since the new gravity dam is located upstream and in the reservoir area of the existing embankment dam, complete drawdown of the existing reservoir would be necessary during construction of this option. Facilities for diversion of streamflows for an extended period of time would also be required. These facilities would be similar to those previously described for Option 2.

Advantages and Disadvantages: The major advantages are: (1) this option restores Penn Forest Dam to its normal operating level; (2) the proposed RCC gravity section relies on the existing embankment for only minimal support such that a minor failure of the embankment section, even though highly unlikely, would not have a significant impact on the overall performance of the dam and (3) this option has the most certainty for a long service life with minimal maintenance. The primary disadvantage of this option is that the reservoir would be completely lowered during construction. A cofferdam located upstream of the work area, as previously described for Option 2, would permit streamflows into the reservoir to be released through the 48-inch conduit into Wild Creek with minimal contamination.

SELECTION OF REMEDIAL OPTION

The estimated total project costs for the three options are:

- **Option 1** - $77.4 million
- **Option 2** - $58.5 million
- **Option 3** - $64.8 million

Option 1 has several drawbacks related to constructibility and performance. Excavation of the wall without damaging the embankment while penetrating hard sandstone layers in the foundation are of particular concern. Option 2 relies on the existing embankment for all of its support which is suspect. While Option 3 is more costly than Option 2, it does not rely on the existing embankment for satisfactory performance. Cost is only one of several important considerations in selecting an alternative. The certainty with which a repair of the dam can be achieved is also important. When considering the overall advantages and disadvantages, costs, risks, and project life, the City of Bethlehem determined it was in their best long-term interest to elect Option 3 and construct a new RCC replacement dam.

CONCLUSIONS

The City of Bethlehem has implemented Option 3 and authorized the design and construction of a new RCC replacement dam. It is expected that the new dam will be completed in 1998 at an estimated construction cost of $45.4 million. The dam will be 160 feet high and 1960 feet long and will contain approximately 380,000 cubic yards of roller-compacted concrete. Penn Forest Dam will be the third largest (by volume) RCC dam in the United States and the largest east of the Mississippi.

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