TIMS FORD DAM, TENNESSEE: REMEDIAL GROUTING OF RIGHT RIM

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Abstract

The Tennessee Valley Authority (TVA) has recently completed a major grouting project at its Tims Ford Dam. Since the first filling of the reservoir in the early 1970s, an increasing amount of seepage has been recorded as flowing through the right rim of the reservoir. The rate of increase accelerated markedly in 1995 -1996 to almost 8,000 gpm, leading to the decision for treatment.

This paper describes the various phases of investigation that were conducted as a prelude to the design and specification of the grout curtain. The selection and properties of the various cement-based compaction and slurry grouts are described, and details are provided of the polyurethane mixes that were foreseen for use. Details are provided for the drilling, permeability testing, and grouting operations. Of particular interest are the details of verification and effectiveness: analysis of permeability and grout hole data, dye testing, seepage flow with time, and reservoir level and piezometric records. The work proved extremely effective and reduced total flows to well under 500 gpm.

Background to the Dam and the Geology

Tims Ford Dam is a 175-foot high compacted rock-fill dam with a sloping impervious rolled earth fill core. It is located on the Elk River about 9 miles west of Winchester, TN, and this TVA structure is multi-purpose, providing flood control, recreation, water supply and peaking power generation. The embankment is about 1,500 feet long and has a crest elevation of 910 feet. At its normal maximum pool elevation of 888 feet, the reservoir comprises an area of 10,600 acres and a total storage volume of about 608,000 acre-feet.

The right (west) abutment of the embankment intersects orthogonally a natural ridge running nearly north-south and rising to Elevations 942 to 958 feet (Figure 1). This ridge comprises overburden above Elevation 900 feet, and various types of limestones, some karstic, below (Figure 2).

The Tims Ford area lies on the southeastern flank of the Nashville Structural dome where it merges into the foreland slope of the Appalachian geosyncline. There has been little structural deformation, and major folds or faults are absent.

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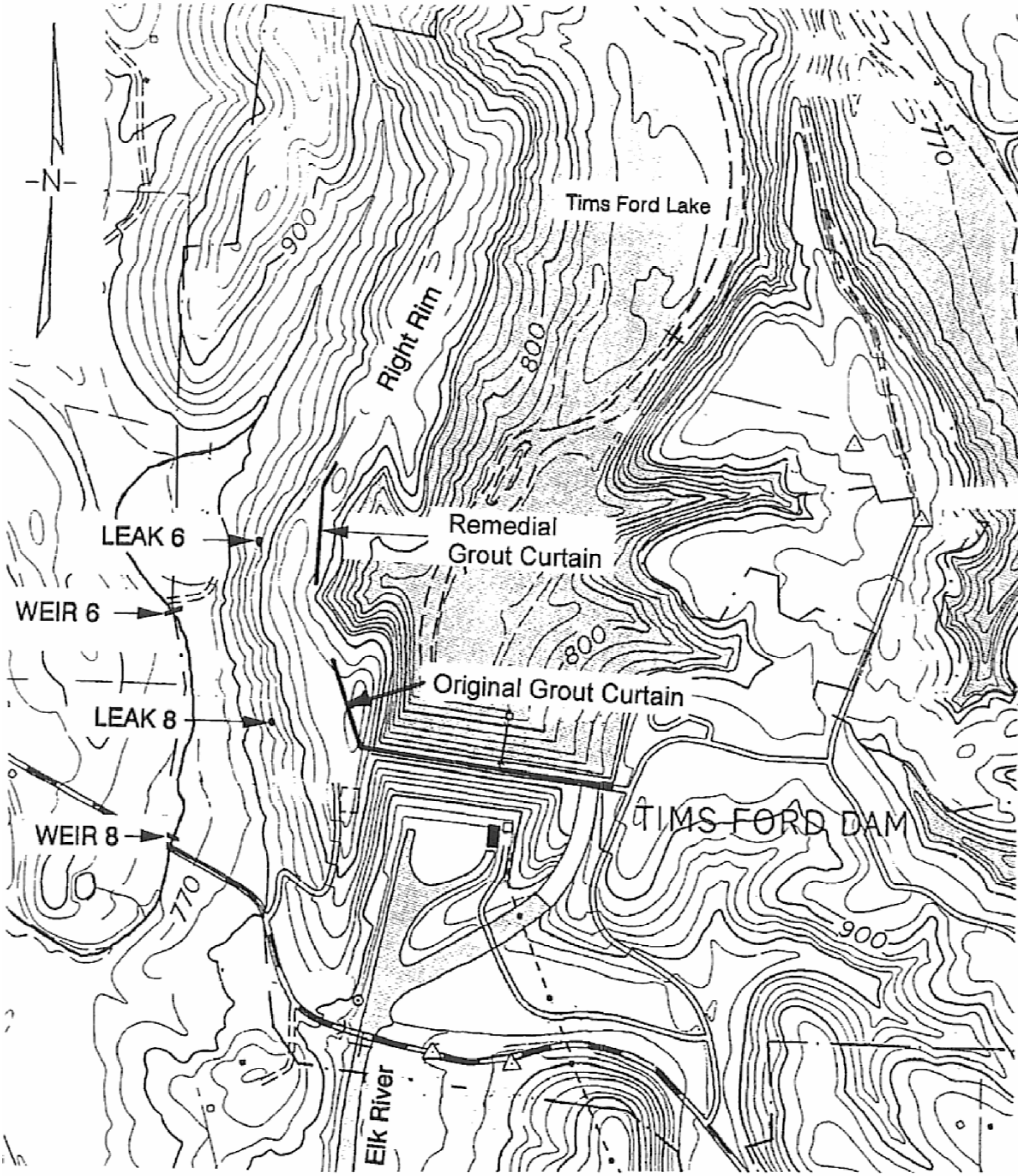


Scale 1" = 1,000 feet

Figure 1. Tims Ford Reservoir plan of dam and reservoir.

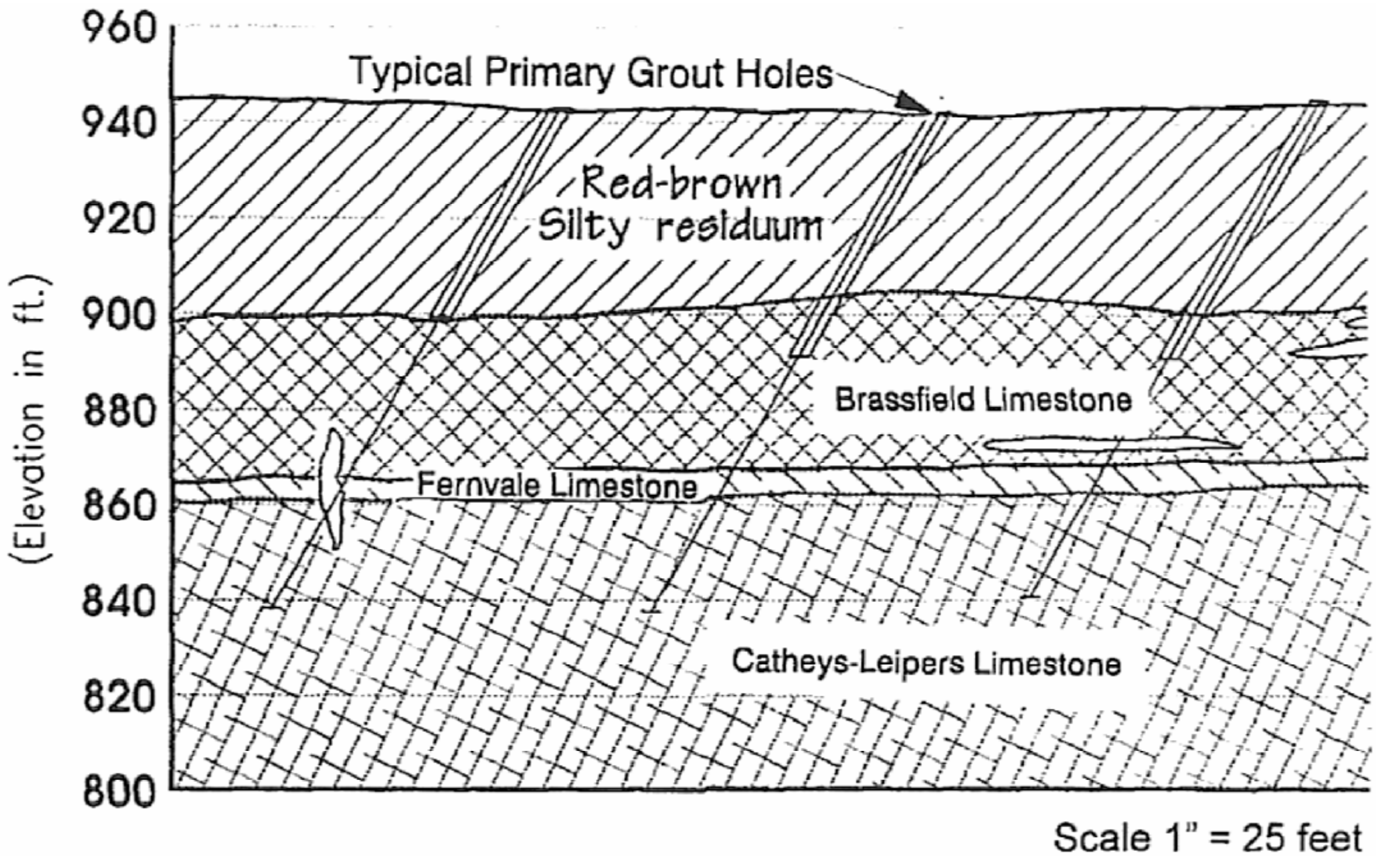


Figure 2. Tims Ford Reservoir simplified geological cross-section.

The Palaeozoic formations present at the right rim were (from top down):

- Residuum from weathering of the Fort Payne Formation: forms the overburden that caps the right rim. It is the youngest formation encountered at the project, and consists of red, cherty clay containing chert blocks that range from 6 inches to 1 foot in diameter. This formation is above normal pool levels.
- Brassfield limestone: a coarse-grained, gray limestone, cherty, shaley, and glauconitic, approximately 27 feet thick, containing numerous solution cavities along bedding planes and near vertical joints.
- Fernvale limestone: a coarse-grained, 11-foot thick layer of gray to red crystalline limestone, also containing solution cavities along bedding planes and joints.
- Catheys-Liepers limestone: a fine- to coarse-grained, gray limestone containing shale lenses and fossiliferous layers and displaying a prominence of clay seams. This is the formation on which the dam is founded.

There are no major faults in the area, although three major vertical joint systems exist at 0, 45°, and 305° azimuths. The local strike is north 50° east, dipping 2° to the northwest.

The Problem

Before construction of the project began, TVA concluded that treatment of the reservoir rims should be delayed pending subsequent evidence of seepage. In October 1966, TVA's Hydro Board of Consultants concurred with the decision to defer "rim treatment" until the necessity was established". Construction began in December 1966 and dam closure was reached on December 1, 1970. In March 1971, when the pool reached approximate Elevation 865 feet, leakage began to develop at several areas on the left abutment and left and right rims.

Leakage developed in two areas along the west side of the right rim (Figure 1), designated Leaks 6 and 8. Leak 8, near Elevation 857 feet, was approximately 150 feet upstream from the projection of the axis of the dam, while Leak 6 was approximately 1,000 feet upstream from the projection of the axis of the dam. The rim at this location is very narrow, being approximately 450 to 600 feet wide. Flowing springs were found adjacent to Leak 6 and included a spring that was active before reservoir filling. Another minor wet area was located 2800 feet upstream of the dam baseline.

In June 1971, as the reservoir neared capacity (Elevation 888 feet), the Board inspected the rim leakage. The Board agreed with TVA's plan of investigations and treatment with grout to reduce flow from the springs to satisfactory levels. Also, because the Board deemed probable with time that other seeps would appear, they recommended "surveillance should be maintained on a reasonable continuing basis".

Rectangular weirs (Weirs 6 and 8) were established on an unnamed tributary to the Elk River to monitor the rim leaks. Flow at Weir 6 was 783 gpm. The discharge characteristics of the rim leakage were very responsive to fluctuations in reservoir levels. Other seeps did appear with time. Leak 9 (now called 8C) was a wet area located approximately halfway between leak areas 8 and 6 at approximate Elevation 860 feet. It developed in June 1972 after treatment for Leak 8 was completed. Spring "E" appeared in 1978 with maximum flows of 140 gpm before subsequently drying up in 1990. A small seep, designated Spring "F" was found in 1979, but soon dried up also. A new leak, designated Spring "G", was observed flowing at about 15 gpm in October, 1985.

In November 1971, the Board suggested a program during the winter season to include further identification of leakage paths, and grouting. They considered "it prudent to plan the avoidance of future possible emergency actions through early advancement of an orderly program directed toward reduction of flow from all observed leaks". Grouting was conducted successfully on the left abutment using cement with calcium chloride accelerator and asphalt. Because of long dye travel time (4 to 8 hours) from drill holes to Leak 6 springs, no grouting was attempted for this area. Flow from leak area 8 was also being reduced by grouting, and TVA decided to extend the grout curtain from the dam baseline along the crest of the right rim.

Leakage did increase steadily at Leak 6, however, reaching approximately 4,000 gpm at maximum pool in 1995 (Figure 3a). However, later that year, following record drawdown of the reservoir, the rate of flow increased dramatically to just under 8,000 gpm at the same pool elevation (Figure 3b). This was followed by a large slide on the hillside around Leak 6, which resulted in several days of muddy flows from the leakage area into the unnamed tributary and the Elk River. Further inspection revealed the overburden at the elevation of discharge was saturated over a 200-foot width of the ridge.

It was reasoned that the annual reservoir fluctuations had resulted in cycles of wetting and drying of the clays and other degenerated material in the features of the limestones. This had made them more susceptible to erosion at high reservoir levels, thus creating larger flow paths and a rapidly increasing overall rock mass transmissivity.

TVA therefore decided in 1996 to treat the right rim, and initially considered three options:

1. Drill and grout from the crest of the rim;
2. Cover the reservoir side opposite the leak with concrete; or
3. Treat the rim on the leakage discharge side.

Option 1 was selected on grounds of cost and constructability, and a target acceptable remnant flow rate of 1,000 gpm at maximum normal pool was set. To facilitate the grouting (i.e., by reducing the hydraulic gradient acting on the rim and so reducing flow rates and velocities), TVA decided to drawdown the reservoir to Elevation 855, equivalent to 10 feet below minimum normal pool.

Investigation and Testing -- 1997 Program

An exploratory drilling and permeability testing program was performed between March and April 1997 to better define the existing foundation conditions, and provide information necessary to design, bid and construct the remedial grout curtain. A total of 17 exploratory holes, mainly inclined, were percussion drilled, permeability tested in stages, and dye tested to establish flow paths and velocities to Leak 6 (Figure 4). Three standpipe piezometers were installed to help gauge the effectiveness of the later grouting. The following major conclusions were reached:

1. Progressive erosion of collapsed and/or desiccated karstic feature infill material was the likely cause of the increased seepage. These features were controlled by solutioning along bedding planes and vertical or near vertical joint sets. Open features in excess of 20 feet deep were detected. Several dye test connection times of only minutes were encountered to the leak.

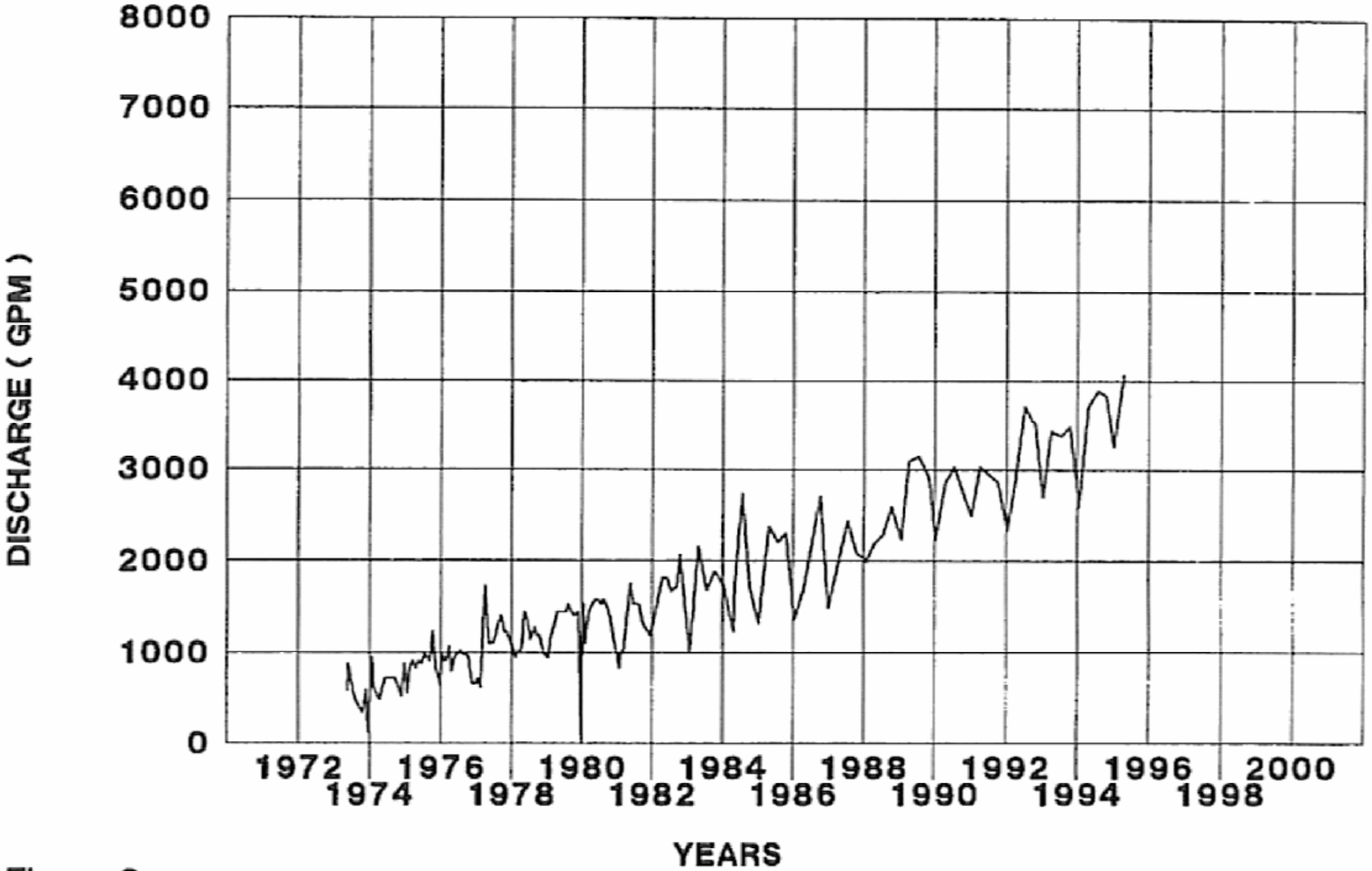


Figure 3a

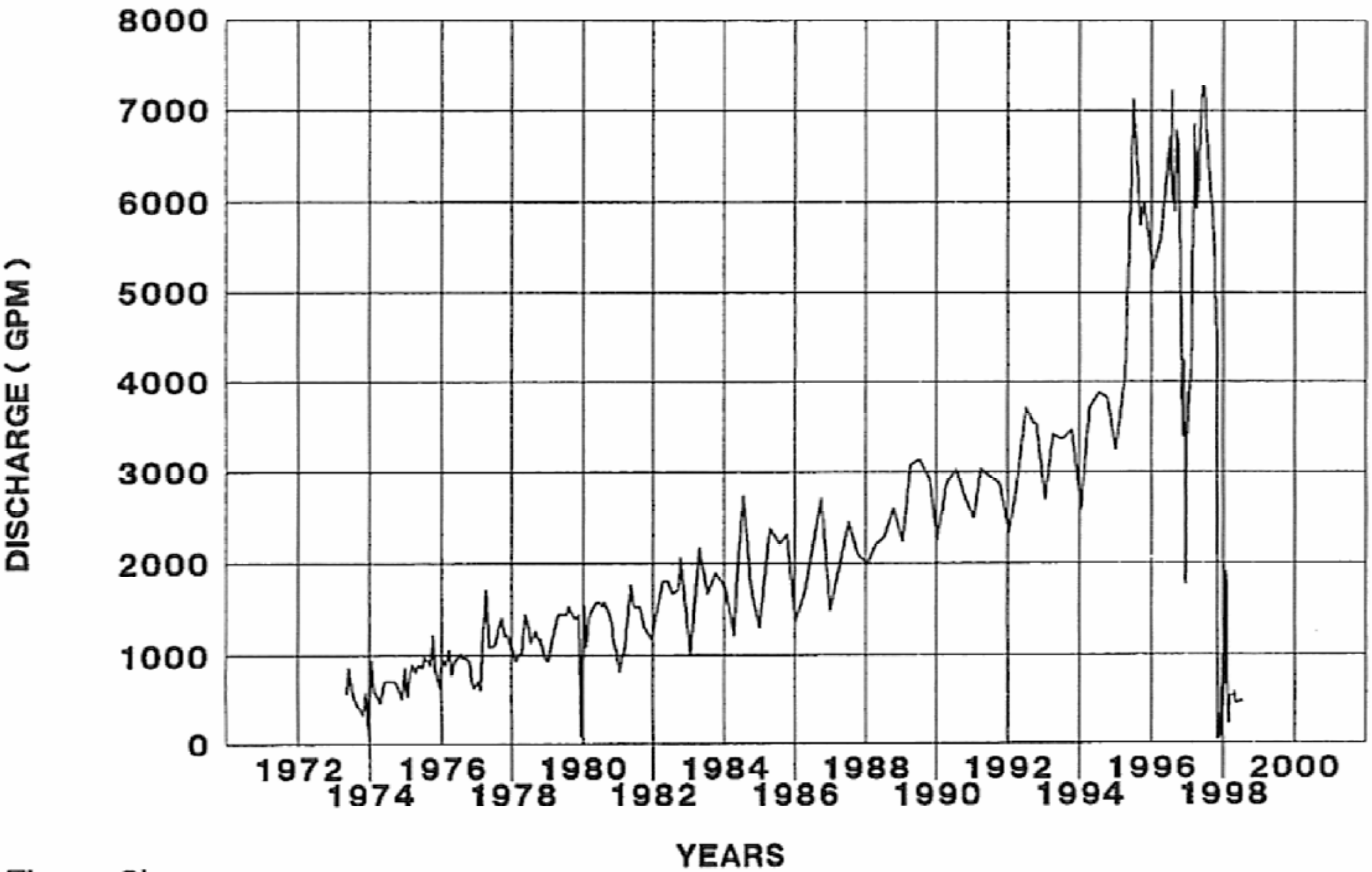


Figure 3b

Figure 3. Tims Ford Reservoir leakage discharge at Weir 6.

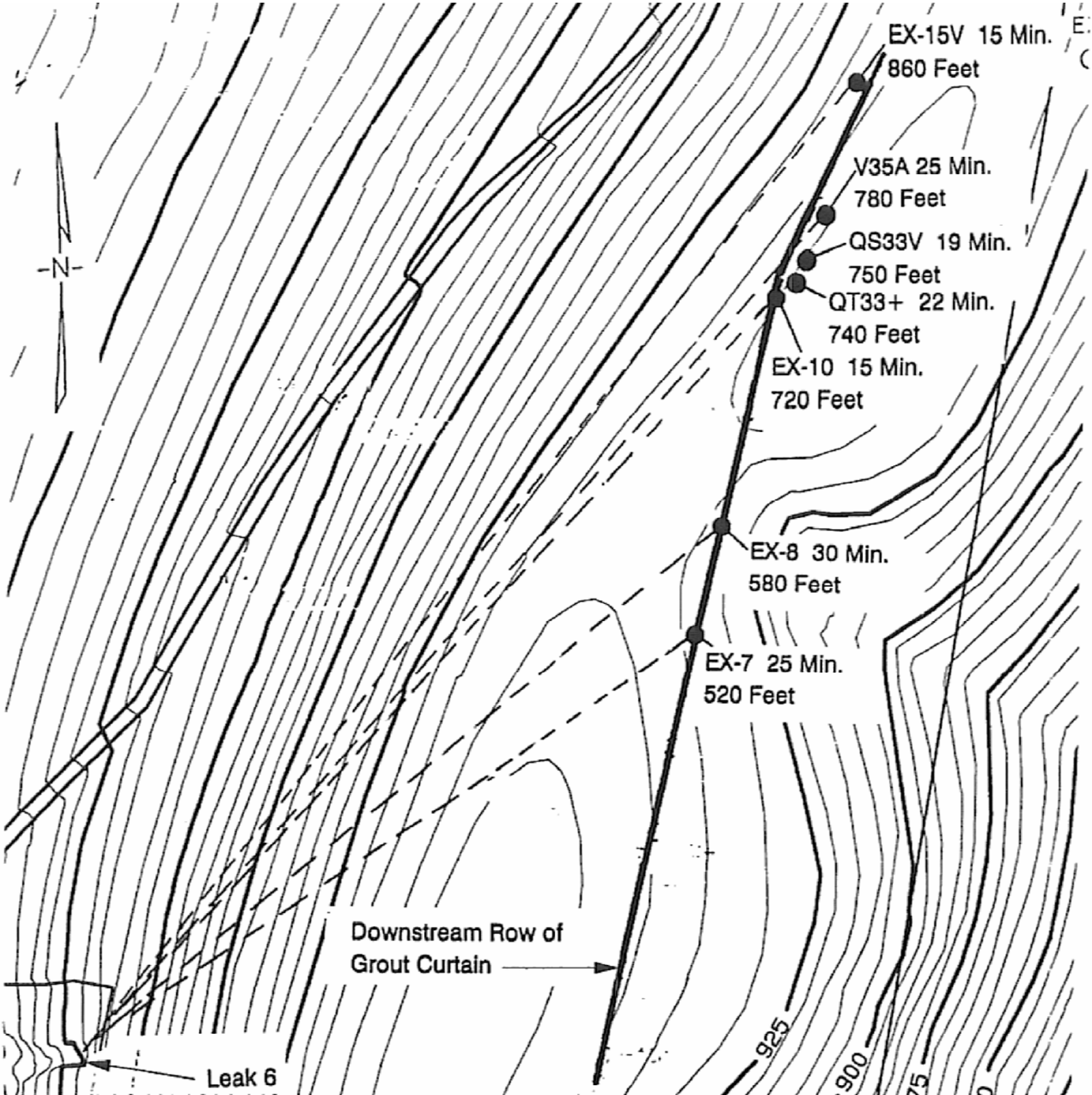


Figure 4. Tims Ford Reservoir plan of flow paths connection times, and distances (minutes and feet).

2. The bottom of the remedial grout curtain as indicated by the geology and permeability, was estimated to be Elevation 840 feet.
3. The southerly extent of the remedial grout curtain was geologically well defined.
4. The middle and north end of the exploratory area was less uniform with high water takes, cavities and open features, very fast dye connection times and the possibility of an undetected open channel to Leak 6. (This possibility of an open channel was reinforced by the occurrence of low permeability areas near the north end on either side of a high permeability area, thus leaving the location of the north end of the curtain somewhat undecided.)
5. There was strong evidence that there would be substantial water flow through the karstic features during remedial grouting.

The Solution

A multirow remedial grout curtain was designed, approximately 800 feet long (Figure 1). The holes were inclined at 30 degrees to the vertical to encourage intersection of (sub)vertical features and were oriented in opposite directions in the two outside rows. Primary holes in each row were foreseen at 40-foot centers, with conventional split spacing methods to be employed (to reduce interhole spacings to 10-foot centers). The central, tightening, row was vertical. The grouting was to be executed between Elevations 888 and 840 feet - locally deeper if dictated by the stage permeability tests conducted prior to the grouting of each stage.

Because of the suspected high flow conditions, the downstream curtain row holes that encountered voids and active flow conditions were designated to be grouted with fast-setting (1 to 3 minute set time) hydrophillic polyurethane resin to provide an initial semi-permanent flow barrier. Holes that did not encounter voids or active flow were to be grouted with cementitious grouts. Upon completion of the downstream row it was anticipated that the active flow conditions would be mitigated, thus allowing the entire upstream row followed by the third, central, closure row to be grouted with cementitious grouts to form a permanent and durable grout curtain. The grouting was designed to be performed using upstage methods although it was anticipated that poor foundation conditions could locally require utilization of downstage methods in conjunction with the polyurethane resin. The grout holes were to be cased through the overburden from the surface to the top of the curtain. The Owner's goal was to reduce the peak seepage to about 1,000 gpm and to focus only on the major features (i.e., not to specifically or systematically treat the smaller fissures).

The Specifications contained provisions that required monitoring and limitations to outflow pH and turbidity to protect the downstream environment. As noted above, TVA agreed to draw down the reservoir to Elevation 855 feet (10 feet below minimum normal pool) to minimize hydraulic gradient and flow through the rim. The curtain was to be constructed by first grouting the far ends, so conceptually channeling the flow through a middle zone which would then be grouted.

Highlights of Construction

As is usually the case in such projects, actual field conditions vary in detail from what was generally foreseen, and this project proved no exception to this rule. The work generally progressed as anticipated, but the following major differences and modifications were made, the latter in full cooperation with the Contractor.

- This project had to observe a very intense schedule due to reservoir drawdown restraints. The schedule required multiple shifts and the ability to drill, at times, with two rigs and to be able to grout with various mixes simultaneously. Drilling of overburden and rock was accomplished with track-mounted diesel hydraulic drill rigs. The overburden casing was installed using rotary drilling techniques, and rock drilling was performed with 3½-inch down-the-hole hammers. The cement grout plant was a high volume colloidal-type mixer fed from bulk cement silos. The grout plant also consisted of two helical screw Moyno pumps so grout holes could be pumped simultaneously. Polyurethane grouts were pumped using a high-pressure piston pump (B-10 Rocker Multi-Component). Compaction grout was batched on site, using a two-conveyor, three-component trailer-mounted batch plant, with hydraulic-driven mixer/conveyor auger. This system of providing the compaction grout mix was supplemented by ready mix trucks dispatched from local ready mix plants. Specially configured high pressure, double piston pumps were used to pump the compaction grout.
- When drawdown of the reservoir reached Elevation 859 feet, the outflow from Leak 6 completely and naturally stopped. As a consequence, much of the grouting work could be done in "no flow" conditions therefore, largely eliminating the need for the polyurethane grouts, and extending the applicability of cement based formulations (including low mobility "compaction" grouts).
- Larger than anticipated open or clay-filled features were encountered especially in the upper 20 feet or so of the curtain. For technical, commercial, environmental and scheduling reasons, such features were treated with a low mobility "compaction grout" (slump 2 to 6 inches; containing also water reducing and antiwashout agents).
- A suite of cement-based grouts were developed to permit the appropriate match of mix design and "thickening sequence" to the particular stage conditions as revealed by drilling and permeability testing (both multi- and single-pressure tests). Details of the initial mixes and their application are provided in Tables 1 and 2.
- In response to conditions revealed during the treatment, observations of the seepage and further dye testing, extra groups of holes were added at the north end of the curtain, including 11 orthogonal to the original curtain, to allow specific treatment of key features.
- About 2,100 cy of compaction grout, 400 gallons of polyurethane, and 790 cy cement based grouts were injected into a total of 250 holes (comprising 11,000 lin. feet of rock drilling).

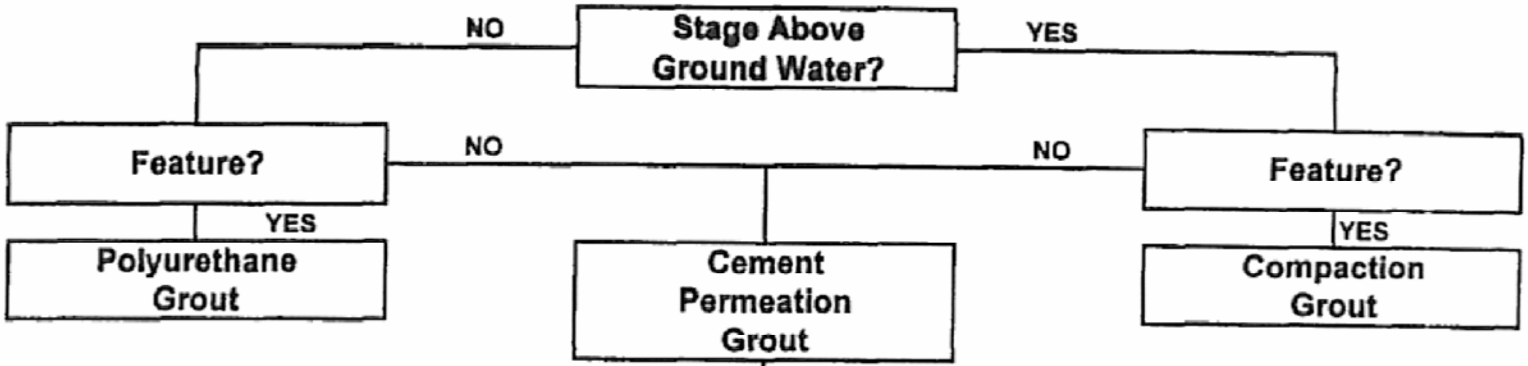
Ingredient	Unit	Mix A	Mix B	Mix C	Mix D
Water	lb	141	141	94	94
Bentonite	lb	4.7	9.4	4.7	4.7
Cement	lb	94	94	94	94
Rheobuild 2000 (water reducing agent)	oz	15	30	20	30
Rheomac UW450 (antiwashout agent)	oz	0	0	0	5
Volume of batch	Gal	20.8	21.0	15.1	15.1
Specific gravity		1.39	1.4	1.53	1.53
Bleed	%	<5	<1	<1	0
Kpf	$min^{-1/2}$	<0.104	<0.042	<0.042	<0.042
28-Day Compress.	psi	500	500	800	800
Marsh time	sec	35	50	60+	100+
Stiffening time	hh:mm	4:30	4:30	4:00	4:00
Hardening time	hh:mm	10:30	8:30	8:00	8:00
Water and slurry volumes					
Bentonite slurry volume	gal	8.0	16.1	8.0	8.0
Additional water volume	gal	9.9	2.8	4.2	4.2

Table 1. Compositions and properties of cement grout mixes, Tims Ford Dam, TN

Verification of Effectiveness of the Treatment

Real-time performance monitoring used during grouting included results from drilling, water tests, calculation of grout hole reduction ratios, and dye testing. This monitoring allowed on-site engineers to track the development of the integrity of the grout curtain and focus grouting efforts on specific zones along the grout rows. Also, the results of the grouting can be demonstrated from data monitored for 1) discharge from the rim leak; 2) groundwater elevations down-gradient from the grout curtain; and 3) headwater elevations.

Engineers used results from water tests to evaluate permeability of the rock in Lugeon values (Lu). The water tests (and drilling) confirmed more open void stages in two certain areas, and higher order holes were added to these zones.



Stage Permeability	Activity
0-1 Lu	Backfill hole with any stable mix
1.1-5 Lu	4 Batches of A Mix 4 Batches of B Mix Begin reducing content of Rheobuild 2000B by 5oz per mix in 2 bag steps for Mix B until refusal or until mix is too thick to mix easily.
5.1-15 Lu	4 Batches of A Mix 4 Batches of B Mix 6 Batches of C Mix Begin reducing content of Rheobuild 2000B by 3oz per mix in 4 bag steps for Mix C until refusal or until mix is too thick to mix easily.
15 Lu +	4 Batches of B Mix 6 Batches of C Mix 10 Batches of D Mix Begin reducing content of Rheobuild 2000B by 3oz per mix in 4 bag steps for Mix D until refusal or until mix is too thick to mix easily. Note: Engineer must be notified when stage approaches refusal or when reduction of Rheobuild 2000B anticipated.

1. Refusal will be defined as a flow of 1 gpm measured over a 10-minute period at the target pressure of 1 psi per foot of depth.
2. No more than 60 batches of cement grout will be injected into a given stage on one 12-hour shift.
3. Compaction grout may be used for filling features below the water table.

Table 2. Flow chart providing guide to mix selection and variation, Tims Ford Dam, TN.

Grout takes closely followed trends observed in the water test data. To evaluate grouting progress, reduction ratios were calculated by dividing the average take of one order of holes by the average take of the previous order of holes. Using this evaluation, grout takes were reduced by 64% from primary/secondary holes tertiary holes (upstream row); by 51% from primary/secondary to tertiary holes (downstream row); and by 63% from quaternary to quinary holes (central row).

As the Contractor began the final stages of the grouting (quaternary and quinary holes were required to fully treat certain problem zones), dye tests were performed to identify connections to the leak and confirm the extent of the curtain. By this time, it was apparent that flow was no longer spread out across the rim, but channeled by the grouting process to the north end of the grout curtain. The evaluation of connections, not only by dye tests, but also by observing washout of grout and turbidity in the leak, were instrumental in achieving the success that was attained under flowing conditions in the features of the karstic limestone. (The reservoir by this time was at elevations above 859 feet.)

The three piezometers installed during the 1997 investigation program were monitored before, during, and after construction of the grout curtain. The piezometers, designated PZ-9, PZ-10, and PZ-11 (Figure 4) were installed down-gradient of the proposed grout curtain to monitor the effectiveness of grouting. At all three piezometers, fluctuations of groundwater levels were influenced by reservoir headwater levels prior to grouting. PZ-11 was grouted up early during construction; PZ-9 collapsed soon after construction was complete; and only PZ-10 continued to provide viable data. On February 16, 1998, while injecting compaction grout into a certain quinary hole that had a strong dye connection to the leak, rim leakage decreased in the course of several hours from 1,075 gpm to less than 60 gpm; groundwater levels measured at PZ-10 dropped about 2 feet and ceased to be influenced by reservoir headwater. PZ-10 continues to remain at reduced levels (Figure 5).

After construction of the grout curtain, TVA measured rim leakage at the normal maximum reservoir elevation in July 1998. Flow was observed as 320 gpm at a temporary weir immediately downstream of the leak head. At long-term Weir 6, discharge was 485 gpm, well within the goal set for this weir of 1,000 gpm. Further downstream, leakage discharge measured at Weir 8 was 583 gpm, reduced from its pre-grouting maximum of 7,772 gpm. Overall rim leakage was reduced in areas other than the immediate area of the grout curtain. In leak area 8, almost 1,000 feet from leak area 6 and the grout curtain, reductions from 162 gpm to 39 gpm were observed at a long-term weir. Monthly inspections of the rim have revealed no breakouts of new leaks, and the previously saturated overburden in the leak area 6 has dried up. The reduction in rim leakage will be monitored over the long term because of the karstic formation containing clay-filled voids that offer the potential for future erosion and increased seepage.

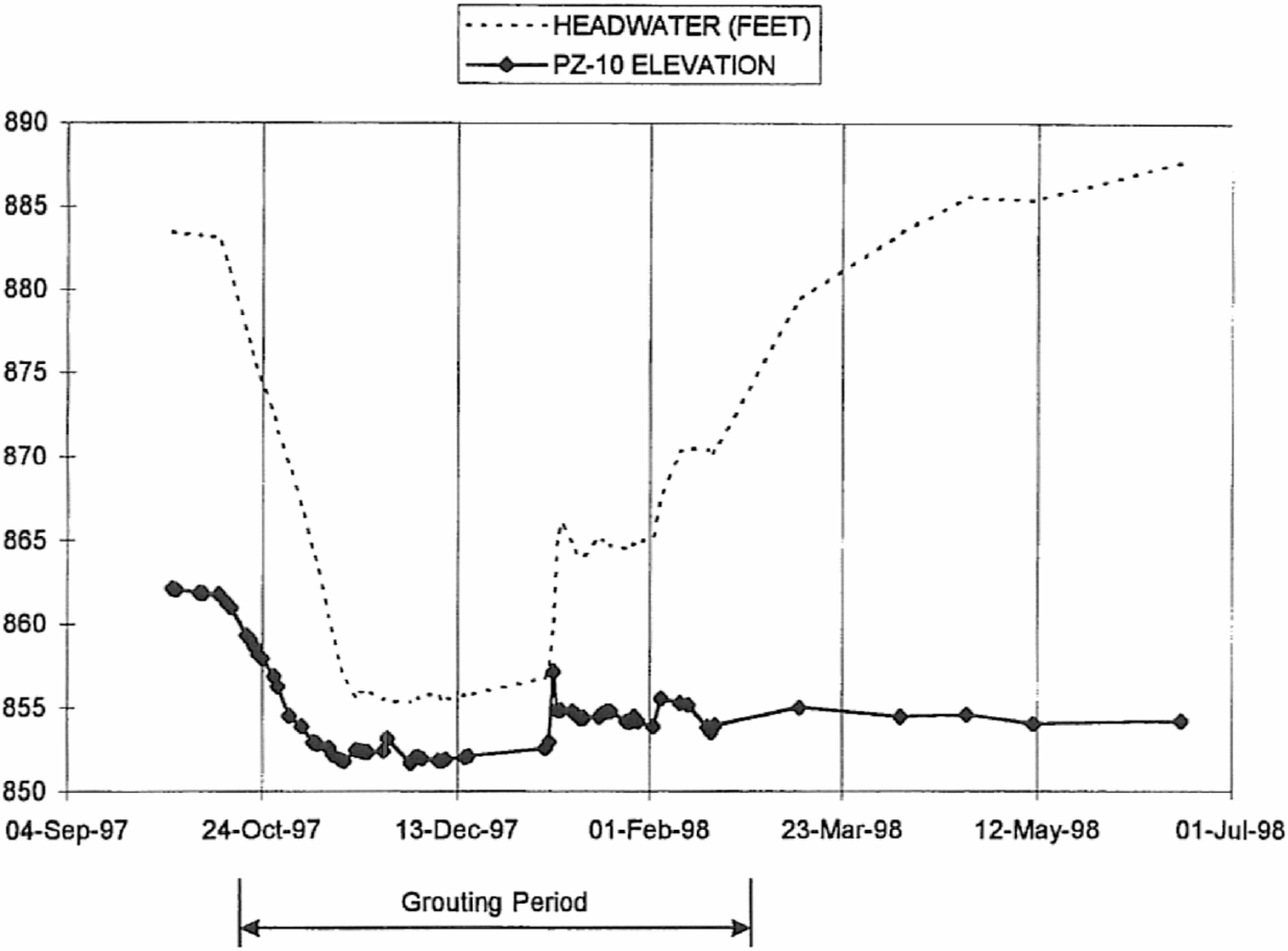


Figure 5. Tims Ford Reservoir Piezometer PZ-10 observations.

Acknowledgements

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