# THE REHABILITATION OF BEAVER DAM: A MAJOR SEEPAGE CUT-OFF WALL

D.A. Bruce * and G. Dugnani†


## Abstract

A major seepage cut off wall was installed through karstic rock at Beaver Dam, Arkansas. Given the geological, hydrological and logistical restraints, this curtain was formed by overlapping 34 inch diameter concrete piles. Special equipment was needed for every phase of the work. Following the construction of the 207,700 square feet cut off, to depths of over 185 feet, the remnant seepage had been reduced by a factor of several hundred. This successful project was undertaken under a Partnering agreement between the owner and the contractor.


## 1. INTRODUCTION

### 1.1 Background

Beaver Dam is located on the White River, in Carroll County, northwest Arkansas. It was constructed for the U.S. Army Corps of Engineers between November 1960 and June 1966. It consists (Figure 1) of a concrete gravity section 1332 feet long, rising to a maximum height of 228 feet above the stream bed, flanked successively to the north by a main zoned embankment 1242 feet long, and three smaller saddle dikes. The top elevation of the flood control pool was originally 1130 feet, and the maximum pool elevation 1137 feet.

### 1.2 The Problem and its Evolution

This paper focuses on Dike 1, adjacent to the north end of the Main Embankment. During the design period, a graben beneath Dike 1 had been identified as a potential problem source, due to the resultant presence of very permeable, highly weathered Mississippian Karstic limestone with clay infilling (Boone Formation). A grout curtain was therefore installed along the center line to contemporary engineering standards.

However, soon after initial filling of the reservoir, seepage was observed at several exit points on the downstream face of Dike 1, totalling 800 gpm. Remedial grouting in 1968-71 succeeded in reducing the flow to about 500 gpm. Clearly the presence in the Boone Limestone of many open, and clay filled, cavities and channels, porous strata, and deep intensely weathered permeable zones, allied to the difficulty of grouting in dynamic water flow conditions had limited the potential effectiveness of the grouting operation.

*Vice President, Nicholson Construction Company, P.O. Box 98, Bridgeville, PA 15017.
†Formerly President, Rodio, Inc., 180 Canal Street, Boston, MA 02114.

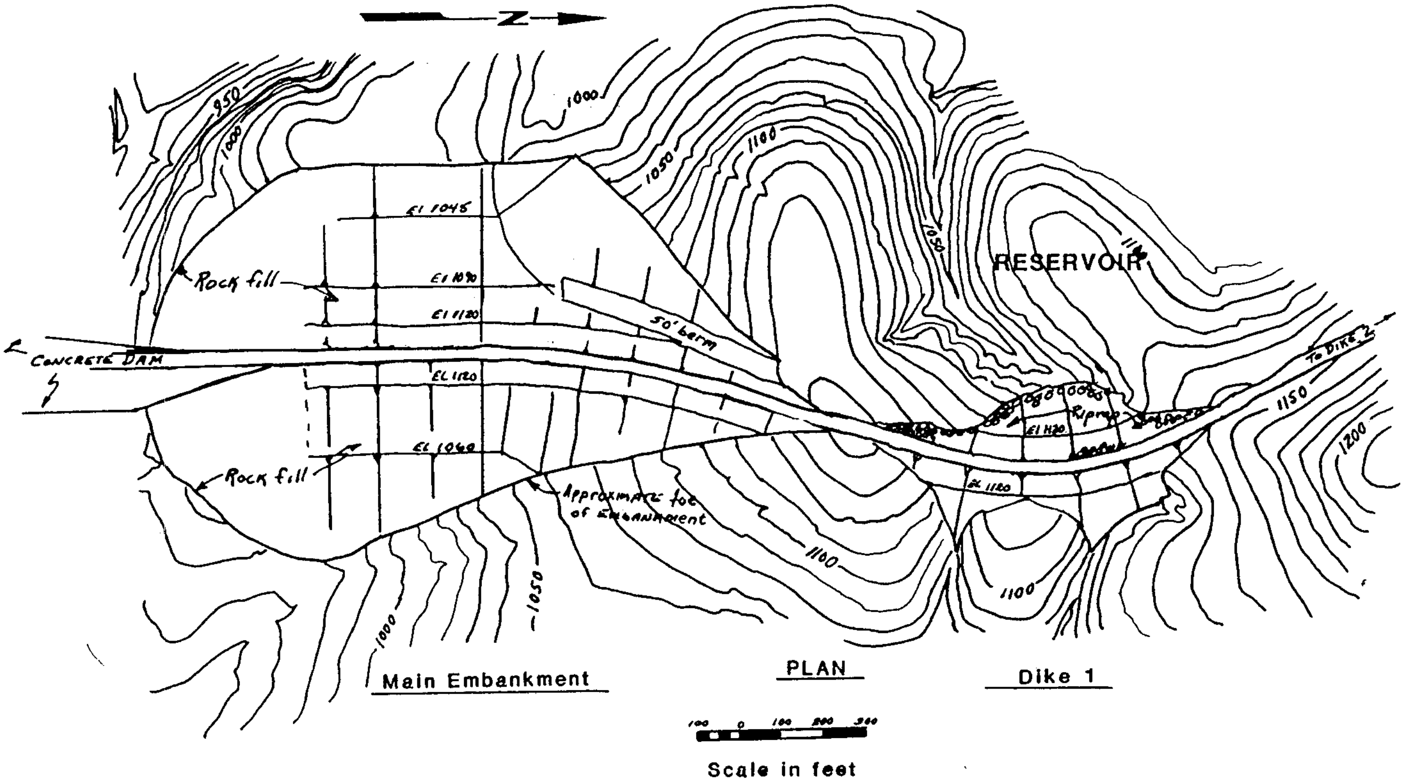



Figure 1. Location of Dike 1 relative to the concrete dam and the Main Embankment (Llopis et al., 1988).

The seepage remained clear, but a new muddy spring was found in December 1984 after a long period of unseasonably heavy rains. Fearing material loss from the Dike, the Corps of Engineers decided to lower the flood control pool level to 1128 feet. This markedly reduced the rate of clear seepage but hardly effected the new dirty flow. In addition, the reduced pool elevation directly affected flood management capacity and restricted generating capacity in the powerhouse in the concrete gravity section. A comprehensive assessment of the seepage issues was published by Llopis et al. (1988).

### 1.3 Concept of Solution

By February 1988, the Corps had designed a "positive" concrete cut-off wall to be installed in the bedrock upstream of the dike, with a depth varying from 80 to 185 feet.

The first attempt to construct a slurry trench type cut off using the rock milling technology of the French-built "12000 Hydrofraise" failed. Apparently, those beds of relatively fresh rock had in situ compressive strengths of over 25,000 psi and could not be excavated economically.

In August 1990, the Corps' Resolicitation of Request for Proposals, led to the award of a contract to the Rodio-Nicholson Joint Venture (RNJV). Their Technical Proposal was based on the concept of forming the wall by secant large diameter concrete piles. This method had been developed (Watakeekul and Coles, 1985) during construction of a similar cut off wall at Khao Laem Dam, on the Quae Noi River, Thailand in 1980-83. The RNJV's proposal foresaw drilling the bedrock with down-the-hole hammers using drill bits of 34 inches in diameter.

Construction of the wall itself began in October 1992 and lasted for 22 months.

## 2. GROUND CONDITIONS

The graben underlies Dike 1 and the contiguous 200 feet of the northern Main Embankment (Figure 2). It is downfaulted about 200 feet between NE/SW trending faults, which now are characterized by zones of disturbed material. Some planes are infilled by a competent breccias or solution deposits. Other fault planes are open and clean.

Under variable thickness of relatively impermeable overburden (typically 15-40 feet) the deeply weathered siliceous and cherty Boone overlies sound rock. The Boone is mainly spongy and chalklike, containing highly irregular tubular and sheet-like cavities, mostly infilled with soft clay containing rock fragments and chert concentrations. The sound rock contains a network of inter-connecting cavities that locally extend down to elevation 974 feet.

Prior to drilling for the cut-off, the upper layers of work platform, embankment and overburden materials were excavated (by slurry wall techniques) to the top of weathered rock, and replaced by concrete. (This was intended to act as a competent, in-situ 4 feet thick, "casing" for the piles when subsequentlypassing through these upper layers. This overburden replacement covered 4713 square yards and consumed 7011 cubic yards of concrete, mainly of 3000 psi strength.)

Figure 3 shows the recorded profile of overburden depth, and the lateral subdivision of the wall, into four "Areas", based on the different geological and construction conditions subsequently encountered.

| Area | Pile No. to Pile No. | Dike St. to St. |
|---|---|---|
| A | 0 - 496 | 62+00 - 72+43 |
| B | 497 - 638 | 72+45 - 75+25 |
| C | 639 - 687 | 75+27 - 76+22 |
| D | 688 - 738 | 76+24 - 77+22 |

## 3. WALL GEOMETRY

As shown in Figure 3, the cut off-wall extends for a total length of 1475 feet from Dike Stn 62+00 to 77+22. It is offset 65 feet upstream of the embankment centerline, and needed a work platform, benched into the upstream face of Dike 1 at elevation 1130 feet. This platform was 65-75 feet wide.

The wall depth varied in response to the geological conditions from 80 to 185 feet although Pile 572 reached 215 feet for exploratory purposes. The total wall area was 207,700 square feet. A total of 24 additional ("conforming") piles were installed, mainly in Areas A and D to assure the required pile overlap at full depth, as identified in Table 1, which also summarizes where coring of piles, and their contacts, was executed for QA/QC purposes.

The individual piles were located at 24 inch centers, yielding (Figure 4) a nominal chordal joint width of 24 inches. This overlapping pile method is executed in two stages:

- in stage 1, a series of "Primary" piles is drilled and concreted;
- in stage 2, the intermediate "Secondary" piles are installed to complete the cut-off.

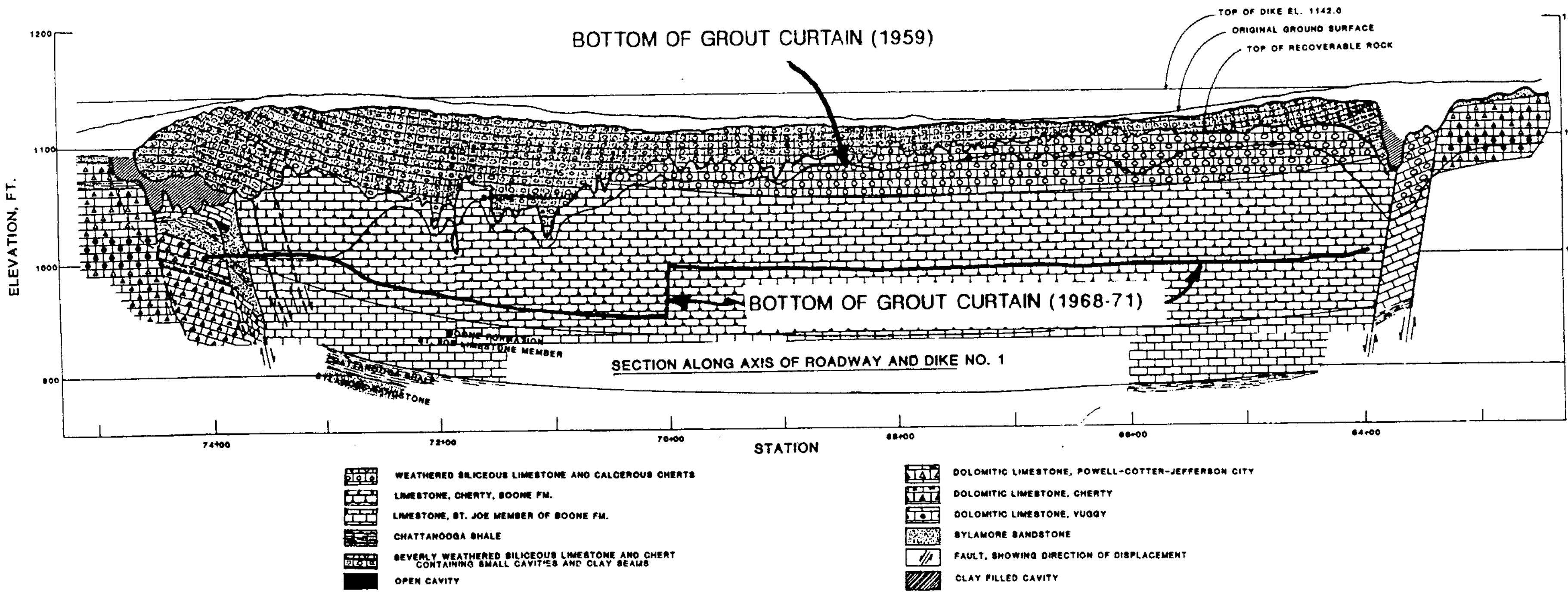



Figure 2. The inferred geology of the graben area underlying Dike 1 (Llopis et al., 1988).

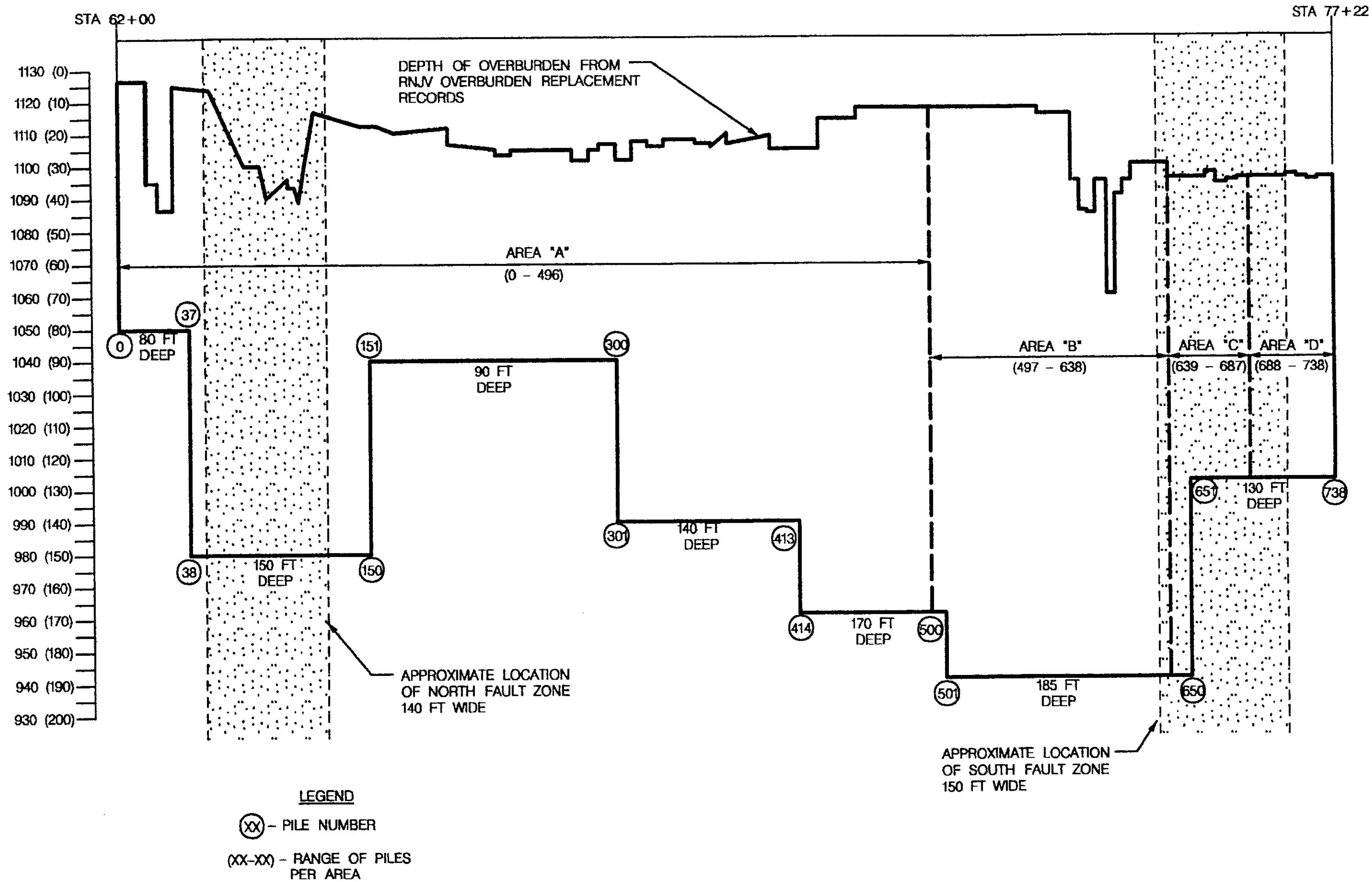



Figure 3. Elevation of the cut-off wall showing main construction parameters.

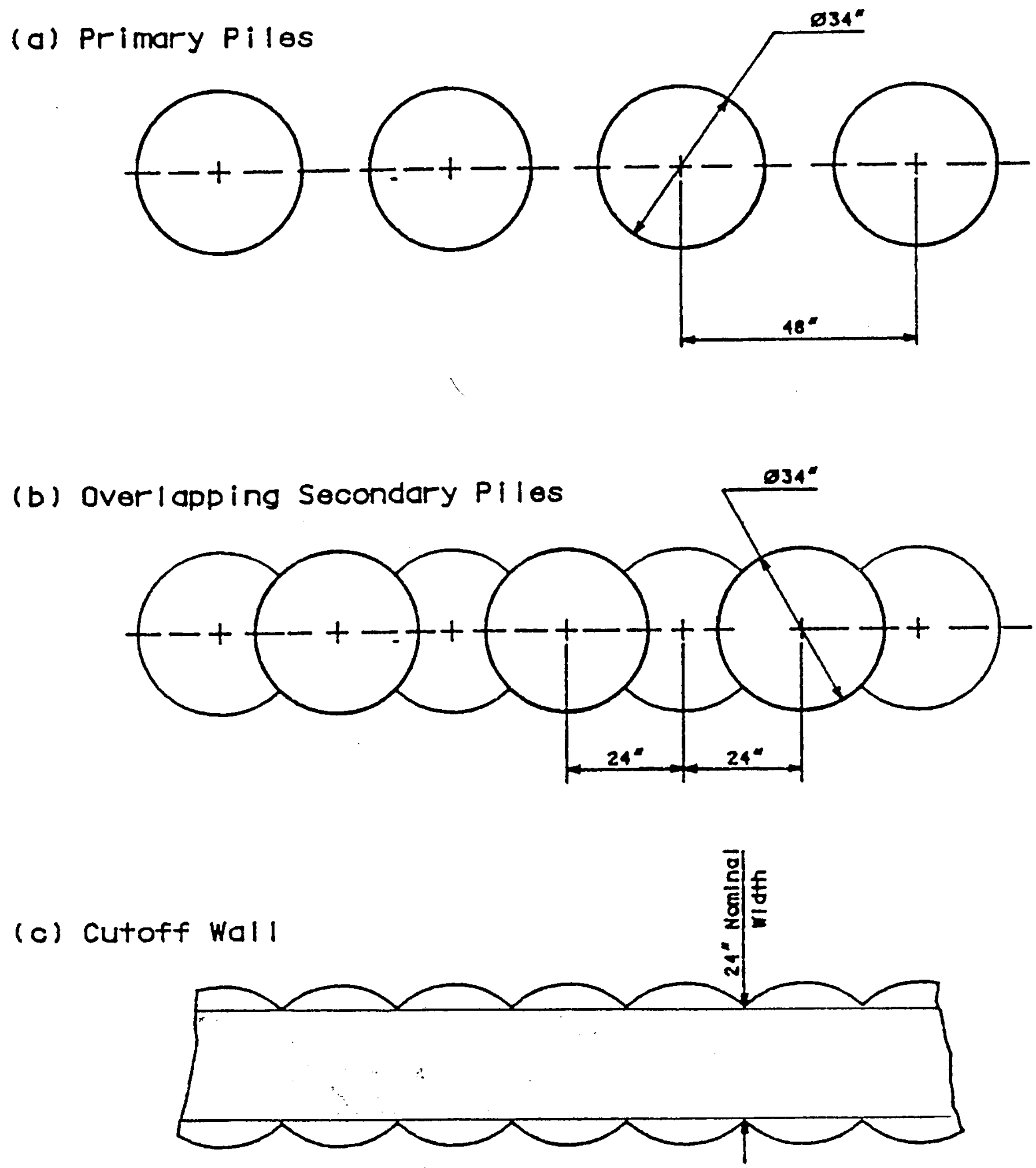



Figure 4. Construction sequence of the cut-off wall.

• Location of Additional "Conforming Piles" (24 ea)

At Piles 26-27; 40-41; 50-51; 55-56; 58-59; 63-64; 68-69; 76-77; 83-84; 93-94; 98-99; 105-106; 135-136; 149-150; 434-435; 489-490; 501-502; 505-506; 512-513; 526-527; 530-531; 544-545; 573-574; 610-611.

• Location of Cored Piles (21 ea)

At Piles 2; 4, 39; 40; 42; 62; 82; 136; 138; 164; 174; 188; 206; 250; 258; 302; 412; 525; 612; 675; 736

• Location of Cored Inter Pile Joints (19 ea)

At Piles 16-17; 46-47; 73-74; 83-84; 140-141; 200-201; 226-227; 264-265; 298-299; 336-337; 368-369; 400-401; 430-431; 470-471; 550-551; 575-576; 616-617-618; 621-622; 719-720

Table 1. Pile numbers subjected to special QA/QC activities.

The following general rules were observed to avoid disturbing nearby piles being drilled, or which had been recently concreted:
- drilling was permitted only beyond a distance of 30 feet from an adjacent open pile not entirely in rock;
- minimum elapse of 48 hours after completion of concreting in a Primary pile before drilling the next successive Primary pile;
- drilling of a Secondary pile only when the concrete of the two adjacent Primaries had reached at least 2000 psi unconfined compressive strength.

## 4. EQUIPMENT

### 4.1 Drilling

Two drill rigs were used for drilling pile holes.
The first, originally used at Khao Laem Dam, had a 100 feet high mast mounted on a Link Belt 318 crawler crane. The crane carried a 200 HP hydraulic power pack powering the Soilmec EC-80 rotary head and other functions, and a drill rod loader. The second machine was designed and built on site and was generally a more powerful evolution of the original, comprising a Manitowoc 4100 crane, a power pack, a Watson rotary head, and two lateral rod changers.

The drill rods were in 30 feet lengths, with an outside diameter of 32 inches and an inner air passage of 11 7/8 inches. Each rig could drill 70 feet in a single pass. Rod rotational speed was varied from 2 to 10 rpm in response to ground conditions.

Different models of air powered down-the-hole hammers - some on trial only - were used. However, the main types, each equipped with a bit 34 inches in diameter, were the Ingersoll Rand DHD130A and the Sandvik XL24. Each hammer was equipped with an internal check valve to allow it to operate underwater. A successful experiment was also made, specifically for penetrating a zone of very abrasive cemented (Sylamore) sandstone, with an Ingersoll Rand CD24-5 cluster drill. This equipment comprised a 24 inch diameter shell, housing five conventional down-the-hole hammers each of 8 inch diameter.

All drilling tools were maintained and fully serviced on site at a facility established by a major subcontractor, Keystone Drilling Services, Inc.

The 150 psi compressed air supply to each hammer was supplied from a bank of nine, static electric-powered compressors each with a volume capacity of 960 cfm at their maximum pressure of 300 psi. They were arranged in two groups of four each, with one spare or supplemental, depending on the individual rig requirements.

Drill penetration rates for Primary piles ranged from 8 to 21 ft/hour (average 14.5), and for Secondaries from 13.5 to 23 ft/hour (average 18). These rates varied considerably from area to area and from rig to rig.

### 4.2 Auxiliary Equipment

The major item was a Link-Belt LS-338 crawler crane for installing and withdrawing concrete tremie pipes. The nearby concrete batching plant and the fleet of truck mixers were finished by another major subcontractor.

Other items included:
- a hydraulic crane, for general lifting
- a truckhoe for digging drainage ditches and settlement ponds
- various payloaders, backhoes, dump trailers, flatbed trailers, tractors, offices and workshops.
- miscellaneous equipment for special activities, such as overburden replacement, pressure grouting, drainage of the platform, and so on.

In addition, there were various QA/QC instruments (in addition to material testing equipment), including:
- the survey and laser systems used for setting up the drill rigs and controlling drill string alignment
- the device for hole verticality control

Other activities were subcontracted, and included preliminary site surveying, electrical installations, concrete coring and testing, and site restoration.

As many as 70 management, supervisory and general labor personnel were involved at the peak of construction in mid 1993.

## 5. CONSTRUCTION

### 5.1 Standard Method

The outline of the standard sequence of pile construction was:

- setting up the drill rig, using theodolites and lasers

- drilling using air pressure commensurate with the local geological conditions. Constant monitoring, and adjustment if necessary, of mast verticality, including after each rod change.
- extraction of rods, and sounding of exact hole depth
- removal, if necessary, by airlift of any soft debris accumulated at the pile toe. This process was enhanced by bucket or grab if larger debris were found.
- verticality of hole verified by a device called a "Submersible Reverse Plumb Bob"
- placement of concrete via 10 inch diameter tremie tubes fed by a 1.5 cubic yard hopper with screen. These tubes were progressively withdrawn during filling, with the toe always embedded 10-20 feet in the concrete.

### 5.2 Special Methods

The many details of the method had been reviewed intensively and agreed by the Corps and the contractor. However, as the work progressed, many changes were made, both in the interests of progressive improvement and efficiency, and in response to unforeseen site and/or geotechnical problems. The more remarkable changes were as follows.

- Down staging: some problems of ground instability were foreseen while drilling through the weathered rock, i.e. below the overburden replacement and above the bedrock. When these instabilities prevented continuous drilling to full depth, the rods were extracted and the pile depth sounded. Following removal, whenever necessary of appreciable amounts (more than 2 feet) of loose material, the hole was backfilled from the surface by concrete. No earlier than 24 hours later, the hole was redrilled through the unstable zone. A total of 71 holes in Area "A" were completed in this way, some requiring three successive treatments. These piles involved 6087 feet of redrilling and 2111 cubic yards of concrete.
- Ground Pretreatment by Pressure grouting: for a 300 feet long section in Area A, a layer of coarse gravel was encountered, and a test grouting operation undertaken over a 120 feet long section. Two rows of holes were installed, 4 feet apart, respectively one foot upstream and downstream of the cutoff. Seven inch diameter steel casings were drilled to the level of "recoverable rock"and cementitious mixes injected during their withdrawal. Totals of 3483 feet of drilling and 282 cubic yards of grout were involved. Thereafter 14 piles were installed in this grouted zone, without the need for downstaging. This trial showed that the principles of grouting could be well employed to fill voids and permeate loose, cohesionless materials in the weathered zone.
- Hole Stabilization by Grouting: during wall construction in Areas B and D, severe problems were posed by the instability of the weathered rock. In Area D, one consequence was settlement of the work platform and the appearance of sinkholes, notably near Piles 690 and 714. The sinkholes were excavated, examined and then backfilled with lean mix concrete, while activities on several other piles under construction in this area were suspended. After much discussion, a modified grouting-based method was selected. The work platform, embankment, overburden, weathered rock, and the top 3 to 5 feet of sound rock were to be treated. Basically, the percussive drilling was interrupted at various depths and the resultant (partial) hole visually inspected. Once the maximum achievable stable depth was identified, the rods were reintroduced, but with a 32 inch diameter rock roller bit at their tip. Grout was then pumped through the rods and bit, and simultaneously mixed with the unstable material, while also

filling voids. In this way, efficient stabilization was achieved in this section of hole. The method was repeated where necessary until stable bedrock was reached, and it proved highly successful in permitting the standard construction methods to be then used to hole completion. A total of 51 Piles in Area D were treated in this way, some requiring as many as six (Pile 714) successive treatments. In total, over 1470 cubic yards of grout were injected plus 132 cubic yards of a concrete used in the more conventional downstaging process in certain piles in less problematical sections.

In Area B, the early piles showed the existence of particularly unstable, weathered rock, containing cavities, voids, and very soft clay pockets in places. This zone ranged from 15 to 90 feet deep. Basically the same method proved in Area D was used there also, with similar success. The process was needed in all the holes in this Area, at least once, and as often as six times (Piles 534 and 550) and, on one occasion (Pile 584), ten times. A total of 4971 cubic yards of grout and 2553 cubic yards of downstage concrete were used, both volumes considerably in excess of neat drilled hole volume, emphasizing the very cavitated nature of the ground in this area.

### 5.3 Concrete

The various concrete mixes used during construction were produced by an automatic batching plant in the immediate project area. It was rated at 200 cubic yards/hour. Transport to the cut off was by means of 9 cubic yard truck mixers. Mixes were varied during the work in response to experiences gained, and strong QA/QC measures were enforced both at the batching plant and at the point of placement for both fluid and set properties. The most commonly used mixes had the following composition (per cubic yard).

| | |
|---|---|
| • Coarse aggregate | 1600-1660 lbs |
| • Fine aggregate | 1280-1363 lbs |
| • Cement | 485-400 lbs |
| • Flyash | 100-130 lbs |
| • Water | 33.0-27.5 gal. |
| • Reducer N | 12-15 oz. |
| • Reducer 1 | 9-0 oz. |
| • Air Entraining Agent | 3.8-2.25 oz. |
| • Calcium | 0-28 oz. |

Water was heated or chilled, depending on the other material, and ambient, temperatures. Final concrete placement data for cut-off wall construction are shown in Figure 5. Total quantities of work conducted are summarized in Table 2.

## 6. EFFECTIVENESS OF THE CUT-OFF

Data were recorded from the existing seepage monitoring instrumentation. Of five seepage areas (SA-1 to SA-5), the area of most concern was SA-1, located in a natural gully 310 feet downstream of the centerline of Dike 1 at Stn 71+00 between Elevation 1052 and 1032 feet. Besides the piezometric network in the three embankments, specific measuring devices were installed to monitor the seepage exiting downstream of Dike 1. The most significant of these were:

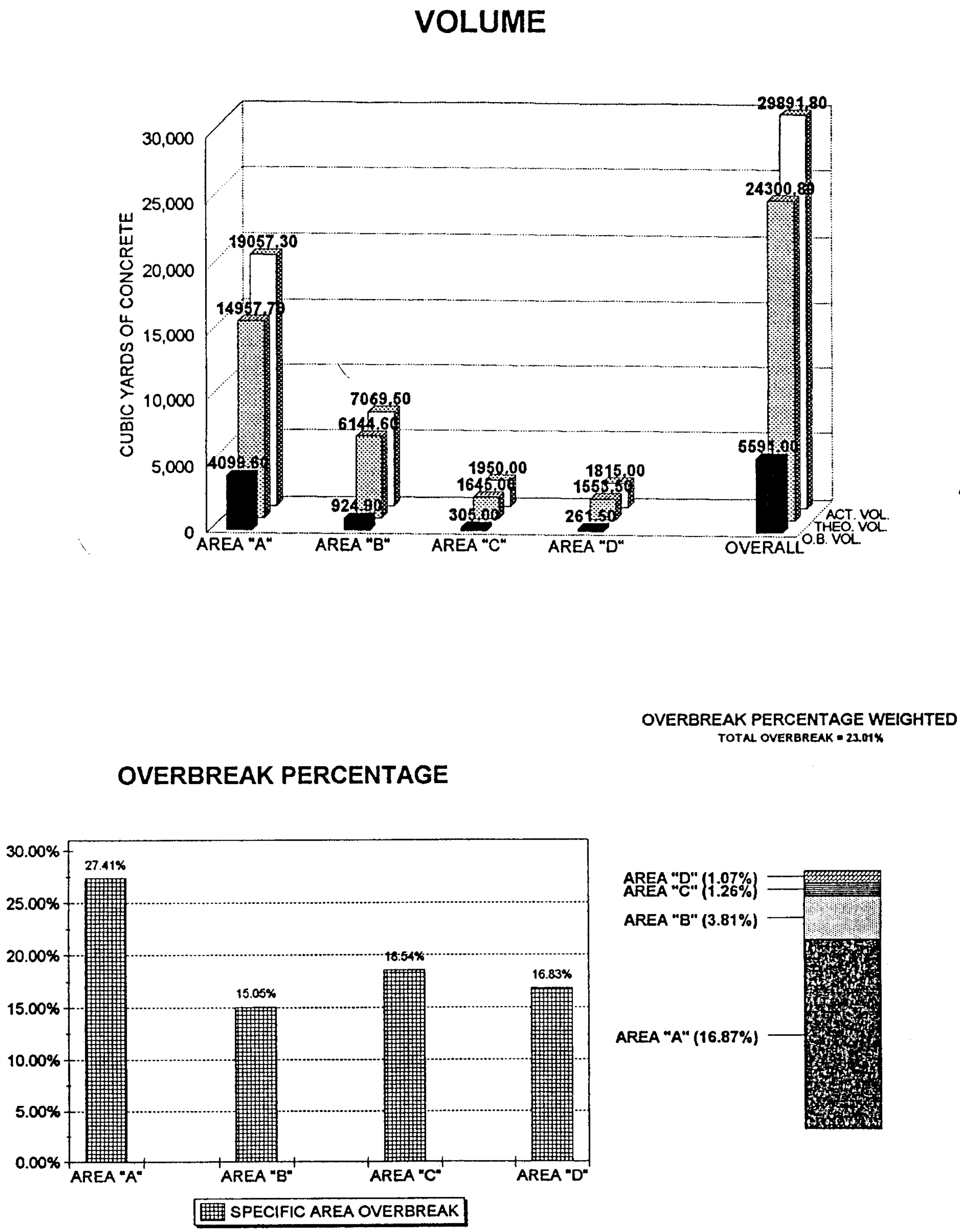



Figure 5. Quantities of final concrete used in the cut-off wall.

| ITEM | DESCRIPTION | AREA PILES NOS. | CUTOFF WALL AREAS AREA "A" 0 - 496 | AREA "B" 497 - 638 | AREA "C" 639 - 687 | AREA "D" 688 - 738 | TOTAL |
|---|---|---|---|---|---|---|---|
| 1 | CUTOFF WALL CONSTRUCTION | | | | | | |
| 1.1 | *DRILLING FOOTAGE DESIGN* | *(ft.)* | *63,543.5* | *26,255.0* | *7,030.0* | *6,630.0* | *103,458.5* |
| 1.2 | DRILLING FOOTAGE ACTUAL | (ft.) | 63,922.0 | 26,259.0 | 7,030.0 | 6,639.0 | 103,850.0 |
| 1.3 | *SURFACE FOOTAGE DESIGN* | *(sq. ft.)* | *127,087.0* | *52,510.0* | *14,060.0* | *13,260.0* | *206,917.0* |
| 1.4 | SURFACE FOOTAGE ACTUAL | (sq. ft.) | 127,844.0 | 52,518.0 | 14,060.0 | 13,278.0 | 207,700.0 |
| 1.5 | SET-UPS | (no.) | 497 | 142 | 49 | 51 | 739.0 |
| 1.6 | CONCRETE VOLUME | (cu. yd.) | 19,057.3 | 7,069.5 | 1,950.0 | 1,815.0 | 29,891.8 |
| 1.7 | *CONCRETE DESIGN THEOR. VOLUME* | *(cu. yd.)* | *14,869.2* | *6,143.7* | *1,645.0* | *1,551.4* | *24,209.3* |
| 1.8 | *CONCRETE O.B. DESIGN VOLUME* | *(cu. yd.)* | *4,188.1* | *925.8* | *305.0* | *263.6* | *5,682.5* |
| 1.9 | *CONCRETE O.B. DESIGN PERCENTAGE* | *(%)* | *28.17%* | *15.07%* | *18.54%* | *16.99%* | *23.47%* |
| 1.10 | CONCRETE ACTUAL THEOR. VOLUME | (cu. yd.) | 14,957.7 | 6,144.6 | 1,645.0 | 1,553.5 | 24,300.8 |
| 1.11 | CONCRETE O.B. ACTUAL VOLUME | (cu. yd.) | 4099.6 | 924.9 | 305.0 | 261.5 | 5591.0 |
| 1.12 | CONCRETE O.B. ACTUAL PERCENTAGE | (%) | 27.41% | 15.05% | 18.54% | 16.83% | 23.01% |
| 2 | GROUT STABILIZATION | | | | | | |
| 2.1 | DRILLING FOOTAGE | (ft.) | 0.0 | 10,667.0 | 0.0 | 2,974.0 | 13,641.0 |
| 2.2 | SET-UPS | (no.) | 0 | 143 | 0 | 60 | 203.0 |
| 2.3 | GROUT VOLUME | (cu. yd.) | 0.0 | 4,971.0 | 0.0 | 1,470.2 | 6,441.2 |
| 2.4 | GROUT THEOR. VOLUME | (cu. yd.) | 0.0 | 2,496.1 | 0.0 | 695.9 | 3,192.0 |
| 2.5 | GROUT O.B. VOLUME | (cu. yd.) | 0.0 | 2,474.9 | 0.0 | 774.3 | 3,249.2 |
| 2.6 | GROUT O.B. PERCENTAGE | (%) | 0.00% | 99.15% | 0.00% | 111.26% | 101.79% |
| 3 | DOWNSTAGING | | | | | | |
| 3.1 | DRILLING FOOTAGE | (ft.) | 4,460.0 | 7,587.0 | 348.0 | 249.0 | 12,644.0 |
| 3.2 | SET-UPS | (no.) | 91 | 116 | 4 | 7 | 218.0 |
| 3.3 | CONCRETE VOLUME | (cu. yd.) | 2,111.0 | 2,553.0 | 199.0 | 132.0 | 4,995.0 |
| 3.4 | CONCRETE THEOR. VOLUME | (cu. yd.) | 1,043.6 | 1,775.4 | 81.4 | 58.3 | 2,958.7 |
| 3.5 | CONCRETE O.B. VOLUME | (cu. yd.) | 1,067.4 | 777.6 | 117.6 | 73.7 | 2,036.3 |
| 3.6 | CONCRETE O.B. PERCENTAGE | (%) | 102.27% | 43.80% | 144.38% | 126.55% | 68.82% |
| 4 | REDRILLING | | | | | | |
| 4.1 | REDRILLING FOOTAGE | (ft.) | 6,087.0 | 18,770.0 | 501.0 | 3,685.0 | 29,043.0 |
| 4.2 | SET-UPS | (no.) | 98 | 211 | 4 | 69 | 382.0 |
| 5 | CONFORMING PILES | | | | | | |
| 5.1 | DRILLING FOOTAGE ACTUAL | (ft.) | 2,380.0 | 1,480.0 | 0.0 | 0.0 | 3,860.0 |
| 5.2 | SET-UPS | (no.) | 16 | 8 | 0 | 0 | 24.0 |
| 5.3 | CONCRETE VOLUME | (cu. yd.) | 623.5 | 374.0 | 0.0 | 0.0 | 997.5 |
| 5.4 | CONCRETE ACTUAL THEOR. VOLUME | (cu. yd.) | 556.9 | 346.3 | 0.0 | 0.0 | 903.2 |
| 5.5 | CONCRETE O.B. ACTUAL VOLUME | (cu. yd.) | 66.6 | 27.7 | 0.0 | 0.0 | 94.3 |
| 5.6 | CONCRETE O.B. ACTUAL PERCENTAGE | (%) | 11.96% | 7.99% | 0.00% | 0.00% | 10.44% |
| 6 | OVERBURDEN REPLACEMENT | | | | | | |
| 6.1 | SURFACE FOOTAGE ACTUAL | (sq. ft.) | | | | | 42,415 |
| 6.2 | VOLUME OF LEAN CONCRETE | (cu. yd.) | | | | | 682.0 |
| 6.3 | VOLUME OF NON-SPEC. CONCRETE | (cu. yd.) | | | | | 6,329.0 |
| 6.4 | TOTAL VOLUME OF CONCRETE | (cu. yd.) | | | | | 7,011.0 |

Table 2. Summary of major work quantities.

Seepage Area SA-1

- Parshall Flume No. 1 - measures flow from SA-1 (Figure 6).
- Parshall Flume No. 2 - measures flow from all the seepages from Dike No. 1 (Figure 6).
- V-notch Weir - measures surface water seepage from SA-1(Figure 7).

Seepage Area SA-2

- French Drain Weir - connects to Parshall Flume No. 2 (Figure 8).
- Artesian Well (Figure 9).

Actual data are provided in Table 3.

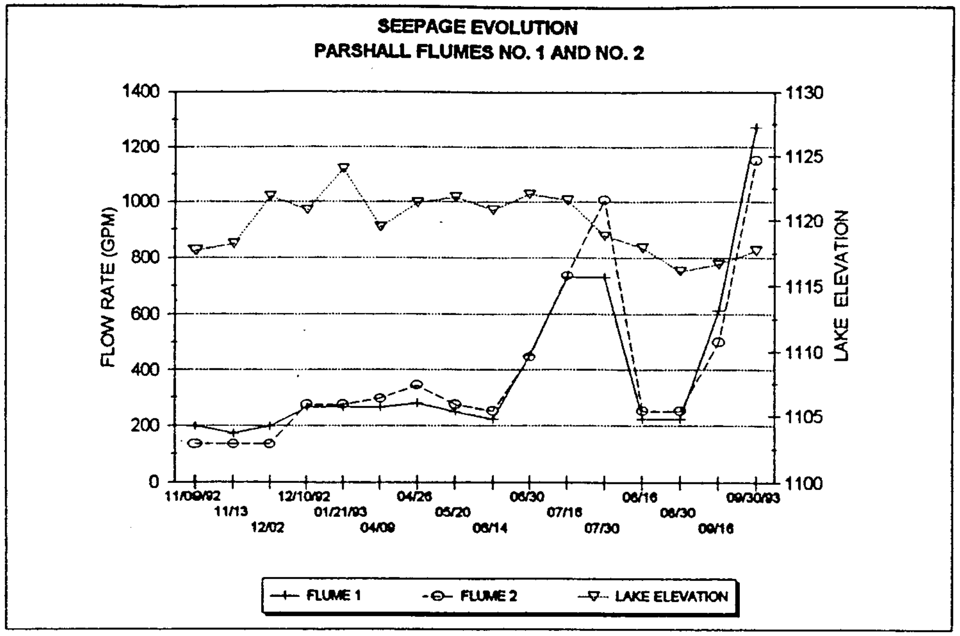
Major observations are:

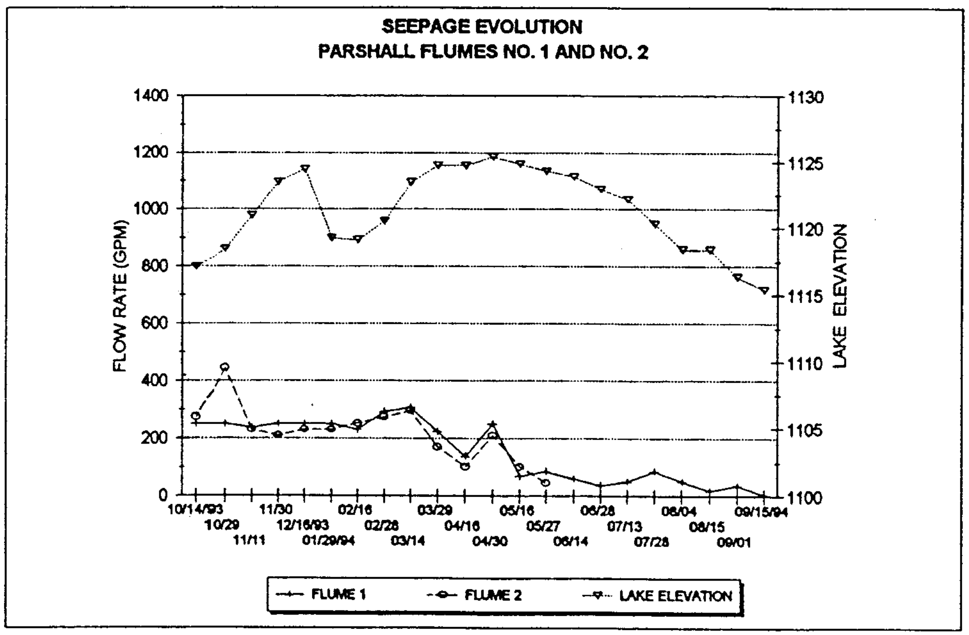
- Parshall Flumes No. 1 and No. 2 - the rise in flows in mid June 1993 was associated with pumping excess surface water from the work platform to the other side (downstream) of the Dike. By mid March 1994, Area D had been completed and the grout stabilization of Area B commenced: flows decreased. By mid September 1994, after surface pumping had ceased, the remnant seepage was barely 4 gpm, compared to a maximum of over 1270 gpm in September 1993.
- V Notch Weir - a sharp decrease ( in both seepage and pumped water) also occurred from mid March 1994 but by late August 1994, when the cut-off was completed, it had totally dried up.
- French Drain Weir - until September 1993 the flow was related to lake level, stabilizing at 3.25 gpm when the level fell below 1118 feet. At the beginning of grout stabilization in Area D in late January 1994, a sharp increase in flow occurred - greater than attributable to lake level fluctuation alone. This suggested a redistribution and concentration of flow paths by the treatment. The flow peaked at 11.64 gpm on March 14, 1994, three days after the completion of Area D. However, by the end of March 1994 the flow had dropped to 2.06 gpm, and eventually dried up totally two weeks later.
- Artesian Well - reacted, with delay to lake level, but showed a 41.35 feet drop in March 1994, despite the rise in lake level. In mid-June 1994 it reached its "drying up" elevation of 1066.2 feet.

In general, these measurements showed that, prior to construction, the seepage was several hundred gallons per minute, varying with lake level. In mid March 1994, when area D was completed and grout stabilization in Area B was commenced, all devices showed a sharp decrease. This trend continued until the completion of the whole wall in August 1994, when all five seepage areas had dried up and the total underseepage was barely 4 gpm.

## 7. FINAL REMARKS

This massive and critical dam rehabilitation project was executed in the face of major geological, logistical and QA/QC challenges. It was completed in a timely fashion to high technical standards, with an outstanding safety record and minimal environmental impact. This excellent result reflects the benefits of the formal Partnering process which was systematically pursued throughout the



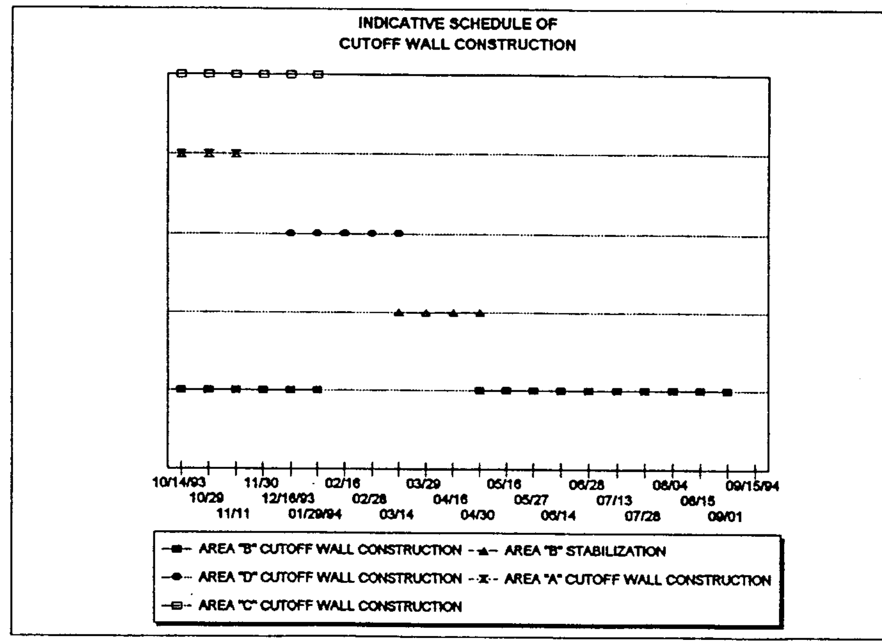
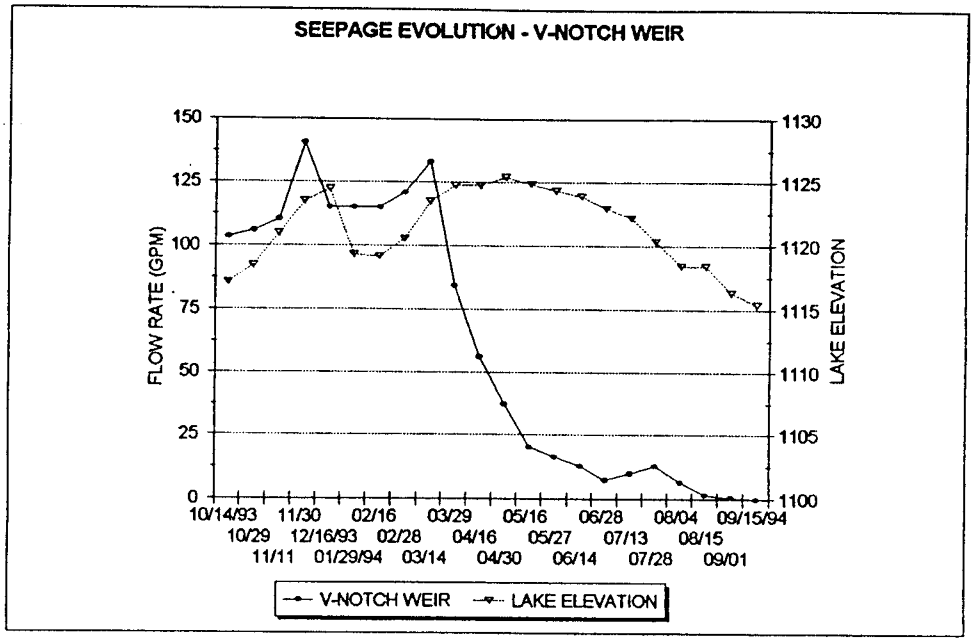




Figure 6. Evolution of seepage volumes: Parshall Flumes No. 1 and No. 2.



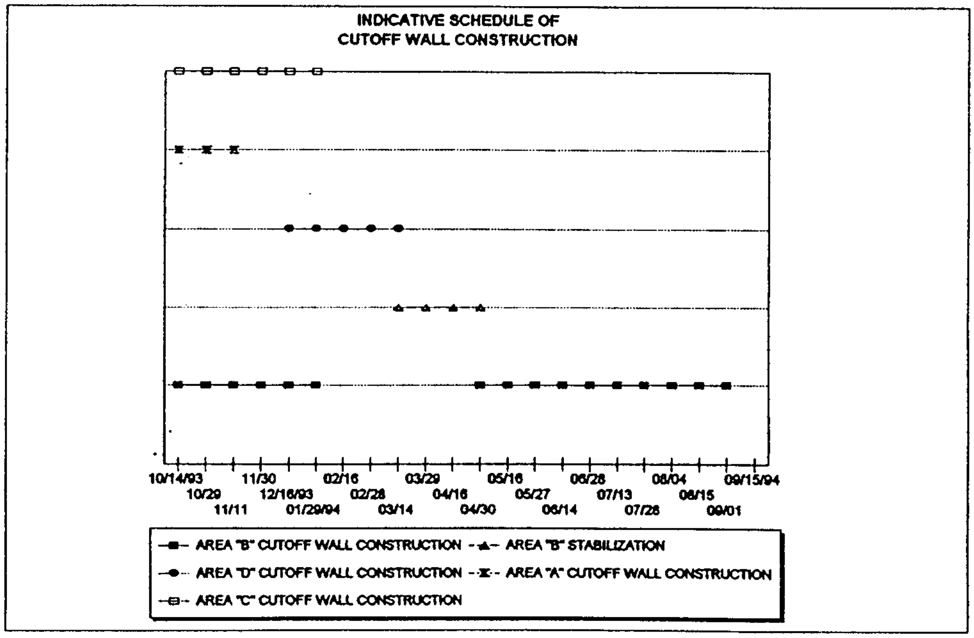




Figure 7. Evolution of seepage volumes: V-Notch Weir.

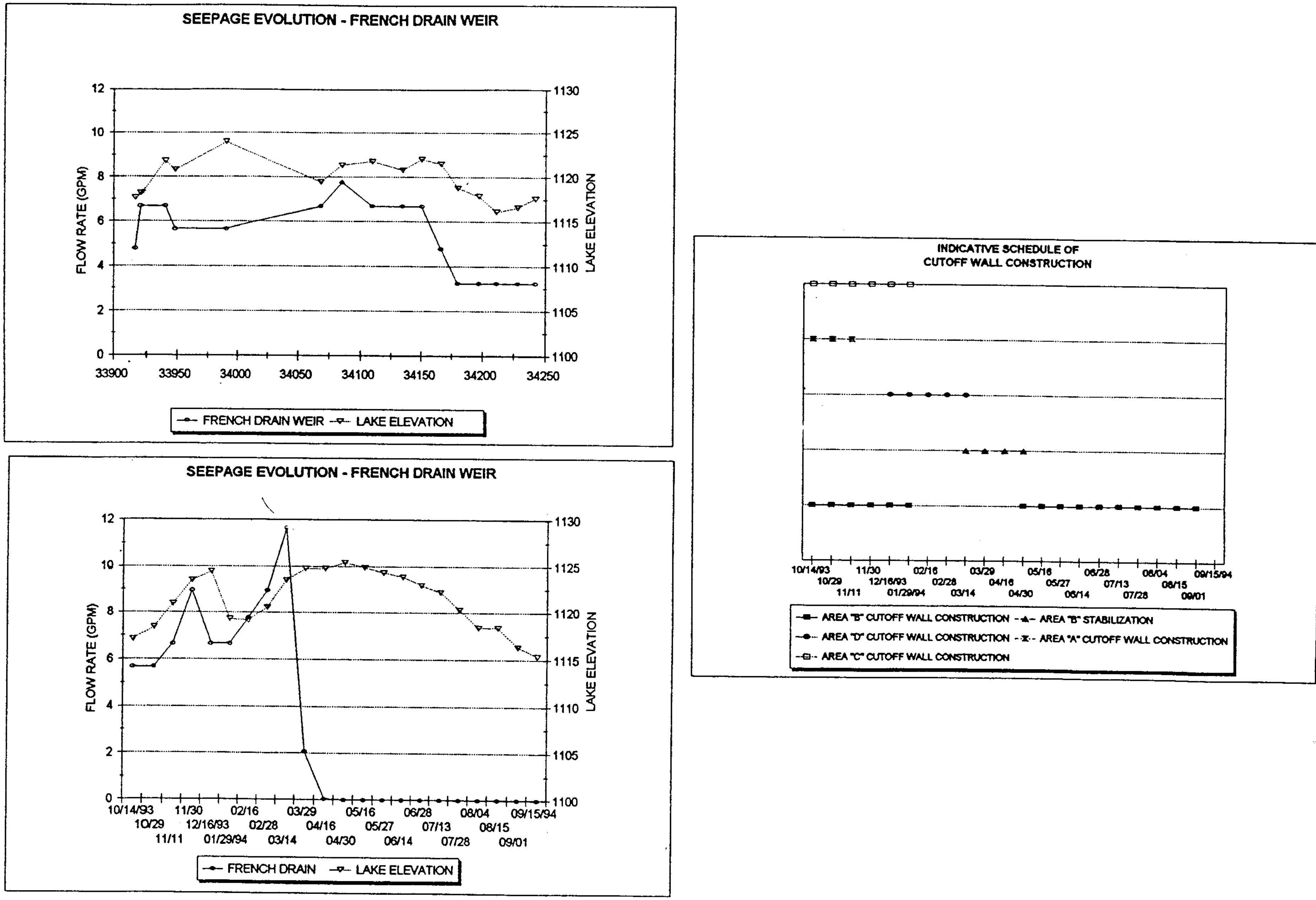
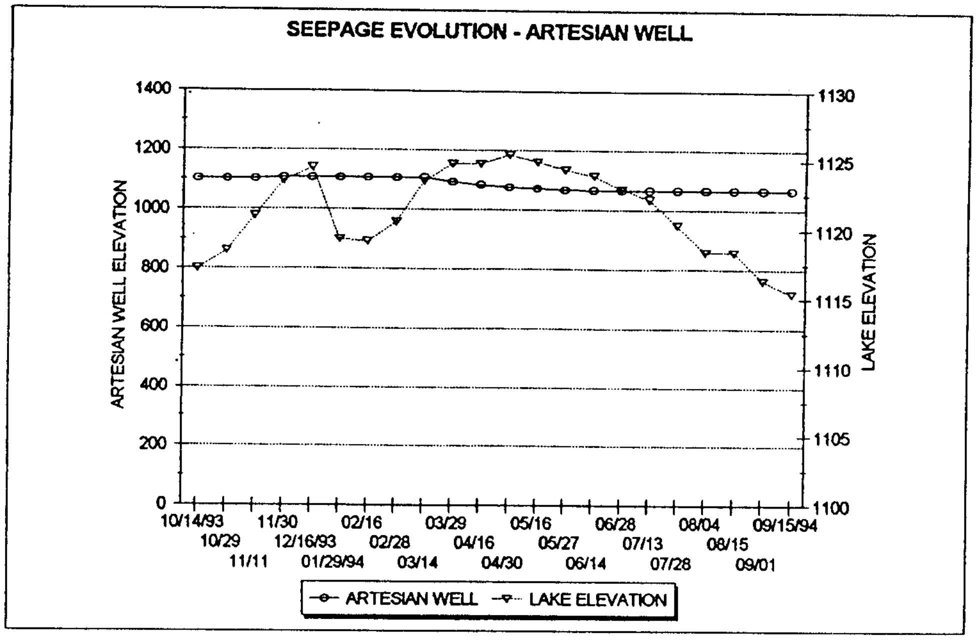



Figure 8. Evolution of seepage volumes: French Drain Weir.



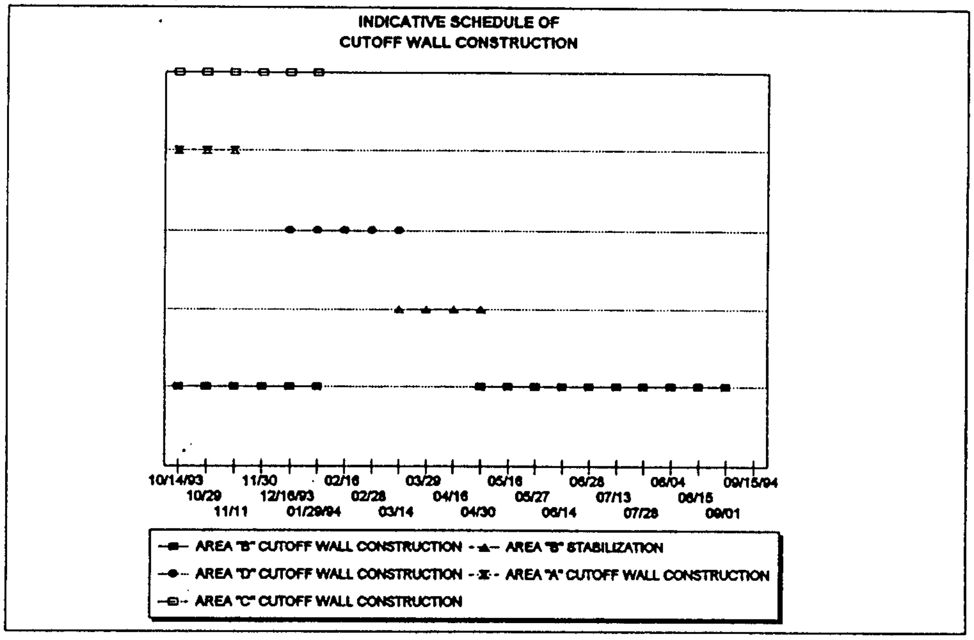




Figure 9. Evolution of seepage: Artesian Well.

| DATE | SEEPAGE AREAS | | | | | SAND | FLUME 1 | | FLUME 2 | | FRENCH DRAIN WEI | | V-NOTCH WEIR | | ARTESIAN WELL | | LAKE | COMMENTS | WEATHER |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | SA-1 | SA-2 | SA-3 | SA-4 | SA-5 | BOIL | FT. | GPM | FT. | GPM | FT. | GPM | IN. | GPM | PSI | ELEV. | ELEVATION | | CONDITIONS |
| 11/09/92 | CLEAR | CLEAR | CLEAR | CLEAR | CLEAR | CLEAR | 0.24 | 196.54 | 0.12 | 134.24 | 0.14 | 4.77 | | | | | 1117.66 | | CLDY |
| 11/13 | CLEAR | CLEAR | CLEAR | CLEAR | CLEAR | CLEAR | 0.22 | 171.74 | 0.12 | 134.24 | 0.16 | 6.66 | | | | | 1118.17 | | CLR COLD |
| 12/02 | CLEAR | CLEAR | CLEAR | CLEAR | CLEAR | CLEAR | 0.24 | 196.54 | 0.12 | 134.24 | 0.16 | 6.66 | | | | | 1121.82 | | CLR COLD |
| 12/10/92 | CLEAR | CLEAR | CLEAR | CLEAR | CLEAR | CLEAR | 0.29 | 263.53 | 0.19 | 273.66 | 0.15 | 5.67 | | | | | 1120.78 | | CLR COLD |
| 01/21/93 | CLEAR | CLEAR | CLEAR | CLEAR | CLEAR | CLEAR | 0.29 | 263.53 | 0.19 | 273.66 | 0.15 | 5.67 | | | | | 1123.97 | | CLR COLD |
| 04/09 | CLEAR | CLEAR | CLEAR | CLEAR | CLEAR | CLEAR ** | 0.29 | 263.53 | 0.20 | 296.31 | 0.16 | 6.66 | | | | | 1119.47 | **SAND BOILS = 8 SMALL ONES | CLR COLD |
| 04/26 | CLEAR | CLEAR | CLEAR | CLEAR | CLEAR | ACTIVE/CLEAR | 0.30 | 277.75 | 0.22 | 343.48 | 0.17 | 7.75 | | | | | 1121.35 | | CLEAR |
| 05/20 | CLEAR | CLEAR | CLEAR | CLEAR | CLEAR | ACTIVE/CLEAR | 0.28 | 249.58 | 0.19 | 273.66 | 0.16 | 6.66 | | | | | 1121.77 | | CLEAR |
| 06/14 | CLEAR | CLEAR | CLEAR | ALMOST DRY | CLEAR | ACTIVE/CLEAR | 0.26 | 222.50 | 0.18 | 251.66 | 0.16 | 6.66 | | | | | 1120.79 | | CLEAR |
| 06/30 | CLEAR | CLEAR | CLEAR | ALMOST DRY | CLEAR | CLEAR | 0.41 | 450.74 | 0.26 | 444.99 | 0.16 | 6.66 | | | | | 1122.02 | RAIN 2-DAYS PREV | CLEAR |
| 07/16 | CLEAR | CLEAR | CLEAR | DRY | CLEAR | CLEAR | 0.56 | 730.81 | 0.36 | 736.91 | 0.14 | 4.77 | | | | | 1121.53 | SA-1 FLOW INCREASE | CLEAR |
| 07/30 | CLEAR | CLEAR | CLEAR | DRY | CLEAR | CLEAR | 0.56 | 730.81 | 0.44 | 1005.76 | 0.12 | 3.25 | | | | | 1118.78 | SA-1 FLOW INCREASE | CLEAR |
| 08/16 | CLEAR | CLEAR | CLEAR | DRY | CLEAR | CLEAR | 0.26 | 222.50 | 0.18 | 251.66 | 0.12 | 3.25 | | | | | 1117.88 | NOT PUMPING | CLEAR |
| 08/30 | CLEAR | CLEAR | CLEAR | DRY | CLEAR | CLEAR | 0.26 | 222.50 | 0.18 | 251.66 | 0.12 | 3.25 | | | | | 1116.12 | NOT PUMPING | CLEAR |
| 09/16 | CLEAR | CLEAR | CLEAR | DRY | CLEAR | CLEAR | 0.50 | 613.08 | 0.28 | 499.16 | 0.12 | 3.25 | | | | | 1116.62 | PUMPING | CLEAR |
| 09/30/93 | CLEAR | CLEAR | CLEAR | DRY | CLEAR | CLEAR | 0.80 | 1270.29 | 0.48 | 1150.98 | 0.12 | 3.25 | | | | | 1117.67 | PUMPING | CLEAR |
| 10/14/93 | CLEAR | CLEAR | CLEAR | DRY | CLEAR | CLEAR | 0.28 | 249.58 | 0.19 | 273.66 | 0.15 | 5.67 | 5.75 | 103.43 | 2.60 | 1102.01 | 1117.12 | | CLEAR |
| 10/29 | CLEAR | CLEAR | CLEAR | DRY | CLEAR | CLEAR | 0.28 | 249.58 | 0.26 | 444.99 | 0.15 | 5.67 | 5.80 | 105.69 | 2.70 | 1102.24 | 1118.42 | PUMPING | CLEAR |
| 11/11 | CLEAR | CLEAR | CLEAR | DRY | CLEAR | CLEAR | 0.27 | 235.90 | 0.17 | 230.32 | 0.16 | 6.66 | 5.90 | 110.31 | 2.80 | 1102.47 | 1120.94 | | CLEAR |
| 11/30 | CLEAR | CLEAR | CLEAR | DRY | CLEAR | CLEAR | 0.28 | 249.58 | 0.16 | 209.67 | 0.18 | 8.95 | 6.50 | 140.52 | 4.20 | 1105.70 | 1123.49 | | PC |
| 12/16/93 | CLEAR | CLEAR | CLEAR | DRY | CLEAR | CLEAR | 0.28 | 249.58 | 0.17 | 230.32 | 0.16 | 6.66 | 6.00 | 115.04 | 4.30 | 1105.93 | 1124.44 | PUMPING ELEV. 1124.5 | CLDY |
| 01/29/94 | CLEAR | CLEAR | CLEAR | DRY | CLEAR | CLEAR | 0.28 | 249.58 | 0.17 | 230.32 | 0.16 | 6.66 | 6.00 | 115.04 | 4.40 | 1106.16 | 1119.28 | NOT PUMPING ELEV. 1118 | CLEAR |
| 02/16 | CLEAR | CLEAR | CLEAR | DRY | CLEAR | NOTE | 0.27 | 229.16 | 0.18 | 251.66 | 0.17 | 7.75 | 0.50 | 115.04 | 4.80 | 1107.09 | 1119.13 | HILLSIDE SEEP NUMEROUS BOILS | CLEAR |
| 02/28 | CLEAR | CLEAR | CLEAR | DRY | CLEAR | DITTO | 0.31 | 292.23 | 0.19 | 273.66 | 0.18 | 8.95 | 0.51 | 120.88 | 4.70 | 1106.86 | 1120.53 | | LT RN |
| 03/14 | CLEAR | CLEAR | CLEAR | DRY | CLEAR | V. ACTIVE | 0.32 | 306.97 | 0.20 | 296.31 | 0.20 | 11.64 | 0.53 | 133.08 | 5.00 | 1107.55 | 1123.47 | | CLEAR |
| 03/29 | CLEAR | CLEAR | CLEAR | DRY | CLEAR | NORMAL | 0.26 | 222.50 | 0.14 | 170.47 | 0.10 | 2.06 | 5.30 | 84.36 | -2.10 | 1093.90 | 1124.75 | | CLDY |
| 04/16 | NOTE | ALMOST DRY | DRY | DRY | CLEAR | LESS ACTIVE | 0.19 | 136.83 | 0.10 | 101.19 | 0.02 | 0.04 | 4.50 | 56.04 | -12.50 | 1083.50 | 1124.75 | TOP OF SA-1 W/O MUCH FLOW | CLEAR |
| 04/30 | NOTE | DRY | DRY | DRY | CLEAR | LESS ACTIVE | 0.28 | 249.58 | 0.16 | 209.67 | 0.00 | 0.00 | 3.83 | 37.45 | -19.50 | 1076.50 | 1125.41 | TOP OF SA-1 DRY : N-RAVINE W/O MUCH FLOW W/ NO PUMPING | T-STORMS |
| 05/16 | TOP DRY | DRY | DRY | DRY | ? | SLGTY ACT | 0.12 | 67.12 | 0.10 | 101.19 | 0.00 | 0.00 | 3.00 | 20.34 | -25.00 | 1071.00 | 1124.87 | | CLDY |
| 05/27 | TOP DRY | DRY | DRY | DRY | ? | LESS ACTIVE | 0.14 | 85.23 | 0.06 | 45.84 | 0.00 | 0.00 | 2.75 | 16.36 | -29.00 | 1067.00 | 1124.31 | | LT RN |
| 06/14 | TOP DRY | DRY | DRY | DRY | DRY | LESS ACTIVE | 0.11 | 58.65 | N/A | N/A | 0.00 | 0.00 | 2.50 | 12.89 | -29.80 | 1066.20 | 1123.89 | | CLEAR |
| 06/28 | DRY | DRY | DRY | DRY | DRY | NO BOILS | 0.08 | 35.80 | N/A | N/A | 0.00 | 0.00 | 2.00 | 7.38 | -29.80 | 1066.20 | 1122.94 | | CLEAR |
| 07/13 | DRY | DRY | DRY | DRY | DRY | 1BOIL | 0.10 | 50.60 | N/A | N/A | 0.00 | 0.00 | 2.25 | 9.91 | -29.80 | 1066.20 | 1122.19 | | CLDY |
| 07/28 | DRY | DRY | DRY | DRY | DRY | 1BOIL | 0.14 | 85.23 | N/A | N/A | 0.00 | 0.00 | 2.50 | 12.89 | -29.80 | 1066.20 | 1120.33 | | CLEAR |
| 08/04 | DRY | DRY | DRY | DRY | DRY | 1BOIL | 0.10 | 50.60 | N/A | N/A | 0.00 | 0.00 | 1.90 | 6.49 | -29.80 | 1066.20 | 1118.4 | | CLEAR |
| 08/15 | DRY | DRY | DRY | DRY | DRY | 1BOIL | 0.05 | 17.28 | N/A | N/A | 0.00 | 0.00 | 1.13 | 1.77 | -29.80 | 1066.20 | 1118.4 | | CLEAR |
| 09/01 | DRY | DRY | DRY | DRY | DRY | 1BOIL | 0.08 | 35.80 | N/A | N/A | 0.00 | 0.00 | 0.75 | 0.64 | -29.80 | 1066.20 | 1116.34 | | CLEAR |
| 09/15/94 | DRY | DRY | DRY | DRY | DRY | 1BOIL | 0.02 | 4.18 | N/A | N/A | 0.00 | 0.00 | 0.00 | 0.00 | -29.80 | 1066.20 | 1115.4 | | CLEAR |

Table 3. Evolution of seepage volumes overall.

project by the owner and the contractor. The open lines of communication and high levels of mutual respect permitted both parties to resolve issues on a daily basis, and to deal optimally with the major challenges as they evolved.

## Acknowledgments

This paper summarizes the efforts of a large number of dedicated and motivated people over a long period: to single out specific contributors would risk causing offense to the great majority, through omission. The organizations who share the credit for this project include the U.S. Army Corps of Engineers (at damsite, Little Rock and Dallas), Rodio (Boston and Milano, Italy), Nicholson Construction Company (Pittsburgh and Atlanta), and various major subcontractors, including Keystone Drilling Services, Inc. (Berlin, PA), and Beaver Lake Concrete, Inc. (Springdale, AR).

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