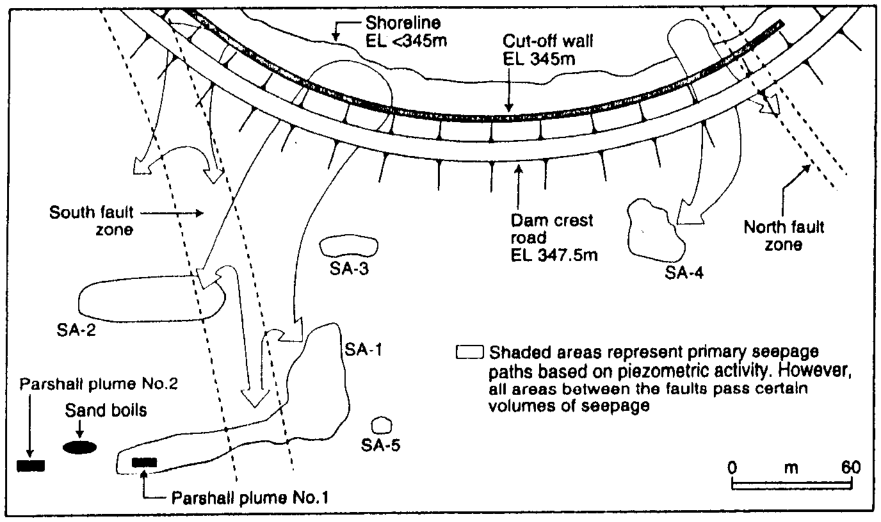
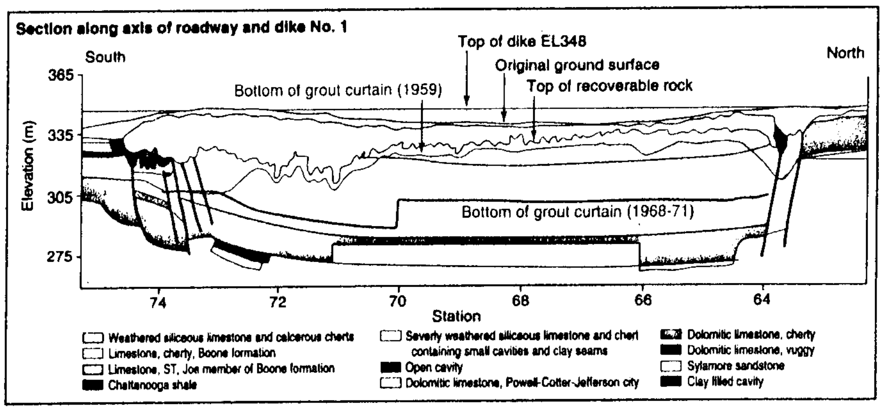
A major seepage cut-off wall has been installed through karstic rock at Beaver Dam, Arkansas. Given the geological, hydrological and logistical restraints, this curtain was formed by overlapping 864mm diameter concrete piles. Special equipment was needed for every phase of the work. Following the construction of the 19,300m² cut-off, to depths of over 56m, 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.





ABOVE RIGHT: Figure 1. Relative positions of dike one, the cut-off wall and the major seepage features. RIGHT: Figure 2. The inferred geology of the graben area underlying dike one (Llopis et al, 1988).

Rehabilitation of Beaver Dam: a major seepage cut-off wall

by DA Bruce & S Stefani.

Beaver Dam is located on the White River, in Carroll County, northwest Arkansas. It was constructed for the US Army Corps of Engineers between November 1960 and June 1966. It consists of a concrete gravity section 406m long, rising to a maximum height of 69m above the steam bed, flanked successively to the north by a main zoned embankment 379m long, and three smaller saddle dikes (**Figure 1**). The top elevation of the flood control pool was originally 344m, and the maximum pool elevation 347m.

This paper focuses on dike one, adjacent to the north end of the main embankment. During the design period, a graben beneath dike one 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 centre 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 one, totalling 50 litres/s. Remedial grouting in 1968-71 succeeded in reducing the flow to about 32 litres/s. 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.

The seepage water 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 US Corps of Engineers decided to lower the flood control pool level to 344m. 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).

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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 24m to 56m.

The first attempt to construct a slurry trench type cut-off using the rock milling technology of the French-built 12000 Hydrofraise failed.

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

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

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 (19ea)

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.

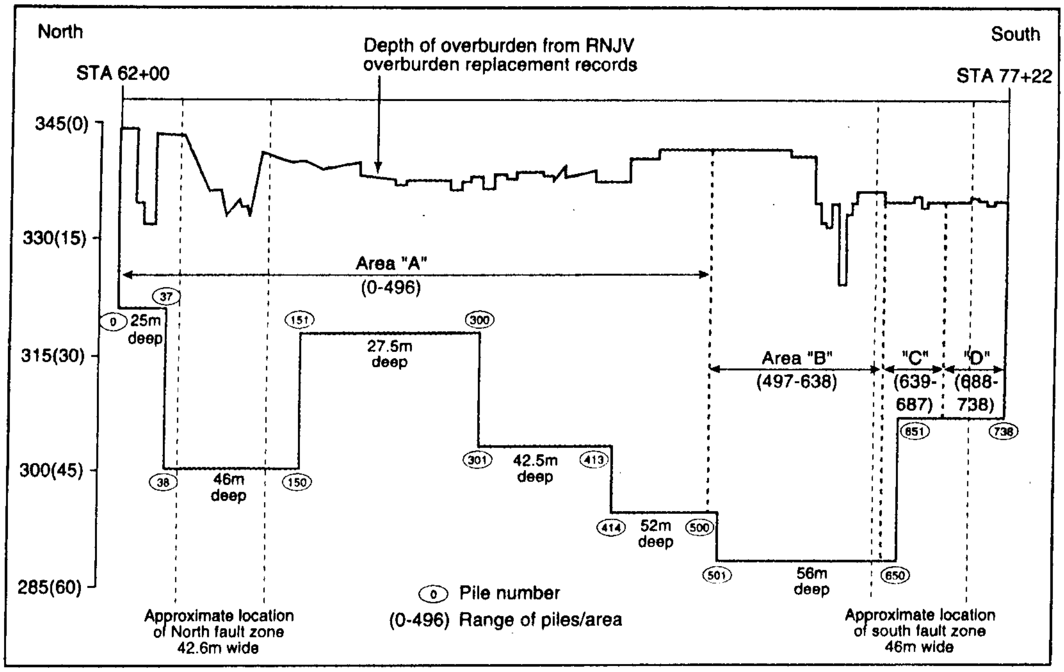


Figure 3. Elevation of the cut-off wall showing main construction parameters.

Drill piling tools.

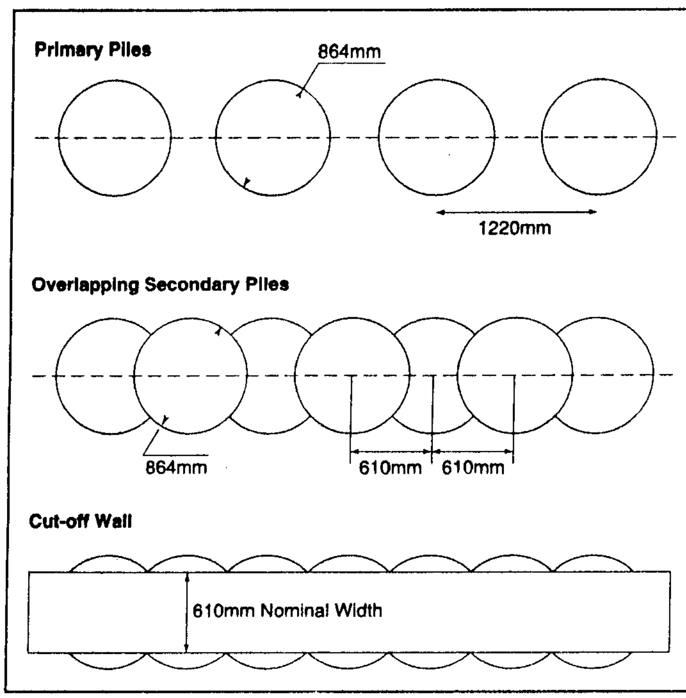


Figure 4. Construction sequence of the cut-off wall.

Apparently, those beds of relatively fresh rock had in situ compressive strengths of over 170MPa 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). Its technical proposal was based on the concept of forming the wall by secant large diameter concrete piles. This method had been developed (Watakeekul & Coles, 1985) during construction of a similar cut-off wall at Khao Laem Dam, on the Quae Noi River, Thailand, in 1980-83. RNJV's proposal foresaw drilling the bedrock with down-the-hole hammers using drill bits of 864mm in diameter.

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

Ground conditions

The graben underlies dike one and the contiguous 61m of the northern main embankment (**Figure 2**). It is downfaulted about 61m between NE/SW trending faults, which now are characterised by zones of disturbed material. Some planes are infilled by competent breccias or solution deposits. Other fault planes are open and clean.

Under variable thicknesses of relatively impermeable overburden (typically 5m-12m), 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 297m.

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 1.2m thick, 'casing' for the piles when subsequently passing through these upper layers. This overburden replacement covered 3941m^2, and consumed 5360m^3 of concrete, mainly 21MPa strength.

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

Wall geometry

As shown in Figure 3, the cut-off wall extends for a total length of from dike stn 62+00 to 77+22. It is offset 20m upstream of the embankment centreline, and needed a work platform, benched into the upstream face of dike one at elevation 344m. This platform was 20m-23m wide.

The wall depth varied in response to the geological conditions from 24m to 56m although pile 572 reached 66m for exploratory purposes. The total wall area was 19,300m^2. 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 summarises where coring of piles, and their contacts, was executed for purposes of quality assurance/quality control (QA/QC).

The individual piles were located at 610mm centres, yielding a nominal chordal joint width of 610mm (**Figure 4**). 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.

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 9m 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 14MPa unconfined compressive strength.

Area	Pile no to pile no	Dike stn to dike stn
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

Table 2. Summary of major work quantities. 1ft = 0.3048m; 1sq. ft = 0.093m²; 1 cu.yd = 0.74m³

			Cut-off wall areas and pile numbers				
Item	**Description**		**Area 'A' 0-496**	**Area 'B' 497-638**	**Area 'C' 639-687**	**Area 'D' 688-738**	**Total**
1	**Cut-off 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 theoretical volume	(cu. yd)	14,869.2	6,143.7	1,645.0	1,551.4	24,209.3
1.8	Concrete OB design volume	(cu. yd)	4,188.1	925.8	305.0	263.6	5,682.5
1.9	Concrete OB design percentage	(%)	28.17%	15.07%	18.54%	16.99%	23.47%
1.10	Concrete actual theoretical volume	(cu. yd)	14,957.7	6,144.6	1,645.0	1,553.5	24,300.8
1.11	Concrete OB actual volume	(cu. yd)	4099.6	924.9	305.0	261.5	5591.0
1.12	Concrete OB actual percentage	(%)	27.41%	15.05%	18.54%	16.83%	23.01%
2	**Grout stabilisation**						
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 theoretical volume	(cu. yd)	0.0	2,496.1	0.0	695.9	3,192.0
2.5	Grout OB volume	(cu. yd)	0.0	2,474.9	0.0	774.3	3,249.2
2.6	Grout OB 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 theoretical volume	(cu. yd)	1,043.6	1,775.4	81.4	58.3	2,958.7
3.5	Concrete OB	cu. yd)	1,067.4	777.6	117.6	73.7	2,036.3
3.6	Concrete OB 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 theoretical volume	(cu.yd)	556.9	346.3	0.0	0.0	903.2
5.5	Concrete OB actual volume	(cu.yd)	66.6	27.7	0.0	0.0	94.3
5.6	Concrete OB 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

Equipment

Two drill rigs were used for drilling pile holes. The first, originally used at Khao Laem Dam, had a 30m 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 changes.

The drill rods were in 9m lengths, with an outside diameter of 813mm and an inner air passage of 302mm. Each rig could drill 21m in a single pass. Rod rotational speed was varied from 2rpm to 10rpm 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 864mm 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 610mm diameter shell, housing five conventional down-the-hole hammers each of 203mm diameter.

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

The 1MPa compressed air supply to each hammer was supplied from a bank of nine, static electric-powered compressors each with a volume capacity of 460 litres/s at their maximum pressure of 2.1MPa. 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 2.4m/h to 6.3m/h (average 4.3m), and for secondaries from 4m/h to 7m/h (average 18). These rates varied considerably from area to area and from rig to rig.

The major item of auxiliary equipment 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 mixes were finished by another major subcontractor, Beaver Lake Concrete Inc.

Other items included:

- a hydraulic crane, for general lifting duties;
- 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; and
- 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 labour personnel were involved at the peak of construction in mid-1993.

Construction

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 was found;
- verticality of hole verified by a device called a Submersible Reverse Plumb Bob;
- placement of concrete via 254mm diameter tremie tubes fed by a 1.1m³ hopper with screen. These tubes were progressively withdrawn during filling, with the toe always embedded 3-6m in the concrete.

The details of the method had been reviewed intensively and agreed by the Corps and the contractor. However, as 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, ie 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 0.6m) 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 1855m of redrilling and 1614m³ of concrete.

Ground pre-treatment by pressure grouting: for a 91m long section in area A, a layer of coarse gravel was encountered, and a test grouting operation undertaken over a 36m long section. Two rows of holes were installed, 1.2m apart, respectively 0.3m upstream and downstream of the cutoff. 178mm

Table 3. Evolution of see
Note: Dates shown in mont

DATE	S	
	SA-1	SA-
11/09/92	CLEAR	CLEA
11/13	CLEAR	CLEA
12/02	CLEAR	CLEA
12/10/92	CLEAR	CLEA
01/21/93	CLEAR	CLEA
04/09	CLEAR	CLE
04/26	CLEAR	CLEA
05/20	CLEAR	CLEA
06/14	CLEAR	CLEA
06/30	CLEAR	CLE
07/16	CLEAR	CLE
07/30	CLEAR	CLE
08/18	CLEAR	CLE
08/30	CLEAR	CLE
09/16	CLEAR	CLE
09/30/93	CLEAR	CLE
10/14/93	CLEAR	CLE
10/29	CLEAR	CL
11/11	CLEAR	CL
11/30	CLEAR	CLE
12/16/93	CLEAR	CLE
01/29/94	CLEAR	CLE
02/16	CLEAR	CLE
02/28	CLEAR	CLE
03/14	CLEAR	CL
03/29	CLEAR	CL
04/18	NOTE	[illegible]
04/30	NOTE	D
05/18	TOP DRY	D
05/27	TOP DRY	D
06/14	TOP DRY	D
06/28	DRY	D
07/13	DRY	D
07/28	DRY	D
08/04	DRY	D
08/16	DRY	D
09/01	DRY	D
09/16/94	DRY	D

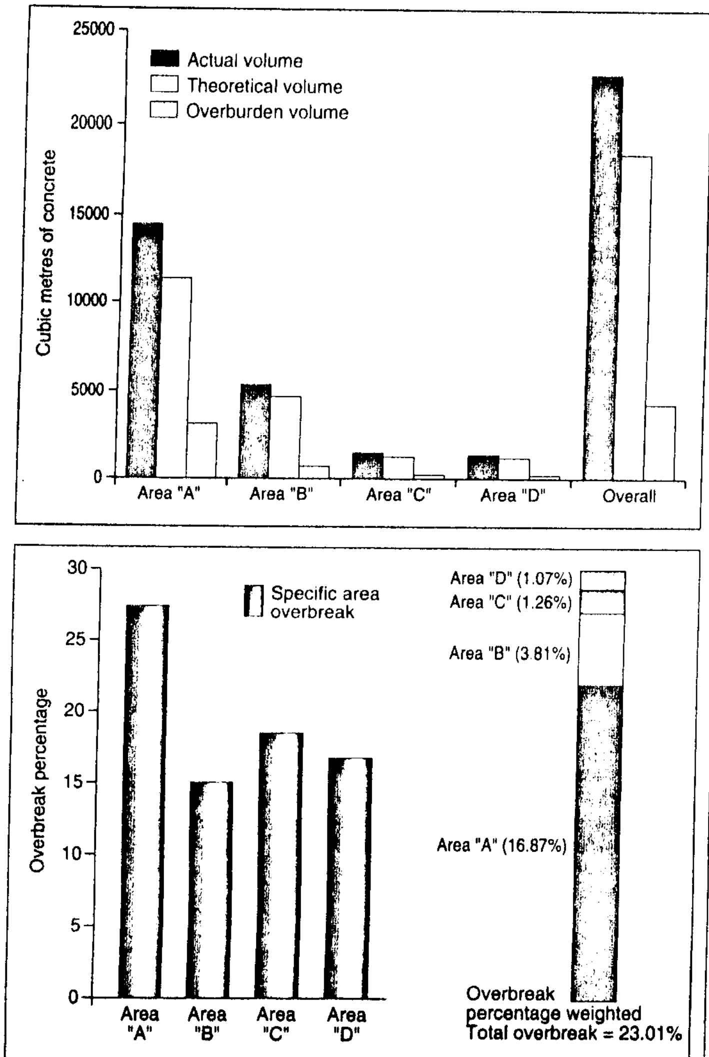
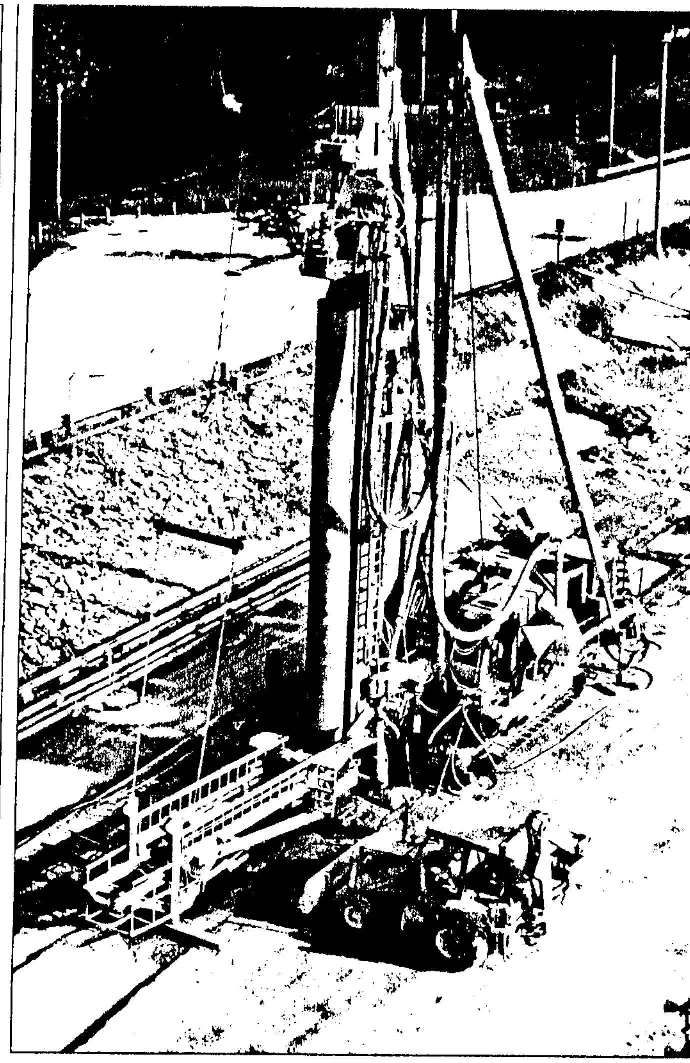


Figure 5. Quantities of final concrete used in the cut-off wall broken down by area, by volume (TOP) and overbreak percentage (ABOVE).

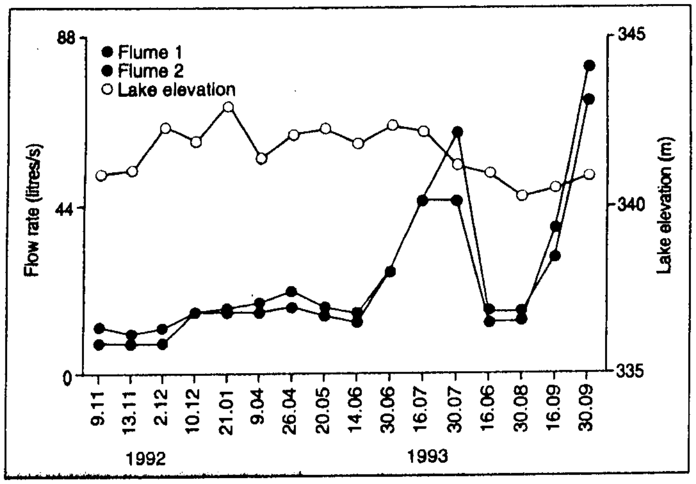


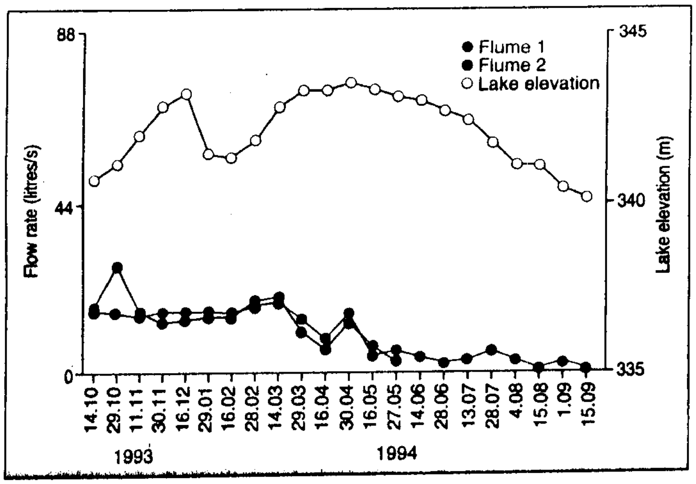
Construction of a cut-off wall.

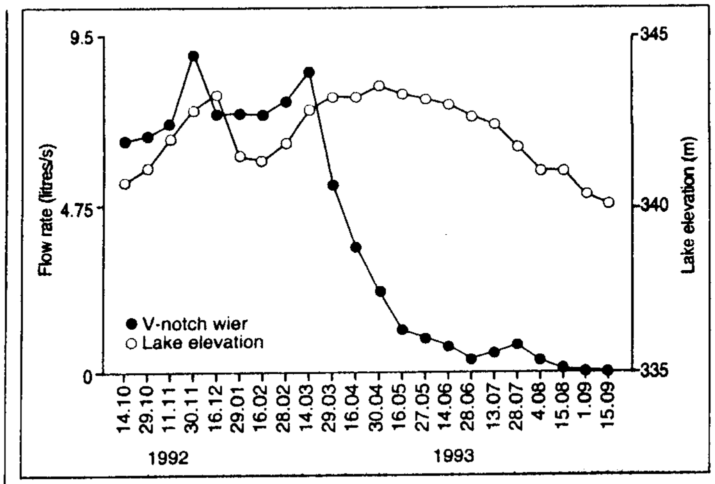
volumes overall. 1ft = 0.3048m; 1sq. ft = 0.093m²; 1 cu.yd = 0.74m³.

/year format.

GE AREAS			SAND	FLUME 1		FLUME 2		FRENCH DRAIN WEI		V-NOTCH WEIR		ARTESIAN WELL		LAKE	COMMENTS	WEATHER
SA-3	SA-4	SA-5	BOIL	FT.	GPM	FT.	GPM	FT.	GPM	IN.	GPM	PSI	ELEV.	ELEVATION		CONDITIONS
LEAR	CLEAR	CLEAR	CLEAR	0.24	196.54	0.12	134.24	0.14	4.77					1117.66		CLDY
LEAR	CLEAR	CLEAR	CLEAR	0.22	171.74	0.12	134.24	0.16	6.66					1118.17		CLR COLD
LEAR	CLEAR	CLEAR	CLEAR	0.24	196.54	0.12	134.24	0.16	6.66					1121.82		CLR COLD
LEAR	CLEAR	CLEAR	CLEAR	0.29	263.53	0.19	273.66	0.15	5.67					1120.78		CLR COLD
LEAR	CLEAR	CLEAR	CLEAR	0.29	263.53	0.19	273.66	0.15	5.67					1123.97		CLR COLD
LEAR	CLEAR	CLEAR	CLEAR **	0.29	263.53	0.20	296.31	0.16	6.66					1119.47	**SAND BOILS = 8 SMALL ONES	CLR COLD
LEAR	CLEAR	CLEAR	ACTIVE/CLEAR	0.30	277.75	0.22	343.48	0.17	7.75					1121.35		CLEAR
LEAR	CLEAR	CLEAR	ACTIVE/CLEAR	0.28	249.58	0.19	273.66	0.16	6.66					1121.77		CLEAR
LEAR	ALMOST DRY	CLEAR	ACTIVE/CLEAR	0.26	222.50	0.18	251.66	0.16	6.66					1120.79		CLEAR
LEAR	ALMOST DRY	CLEAR	CLEAR	0.41	450.74	0.26	444.99	0.18	6.66					1122.02	RAIN 2-DAYS PREV	CLEAR
LEAR	DRY	CLEAR	CLEAR	0.56	730.81	0.36	736.91	0.14	4.77					1121.53	SA-1 FLOW INCREASE	CLEAR
LEAR	DRY	CLEAR	CLEAR	0.56	730.81	0.44	1005.78	0.12	3.25					1118.78	SA-1 FLOW INCREASE	CLEAR
LEAR	DRY	CLEAR	CLEAR	0.26	222.50	0.18	251.66	0.12	3.25					1117.88	NOT PUMPING	CLEAR
LEAR	DRY	CLEAR	CLEAR	0.26	222.50	0.18	251.66	0.12	3.25					1116.12	NOT PUMPING	CLEAR
LEAR	DRY	CLEAR	CLEAR	0.50	613.08	0.28	499.16	0.12	3.25					1116.62	PUMPING	CLEAR
LEAR	DRY	CLEAR	CLEAR	0.80	1270.29	0.48	1150.98	0.12	3.25					1117.67	PUMPING	CLEAR
LEAR	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
LEAR	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
LEAR	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
LEAR	DRY	CLEAR	CLEAR	0.28	249.58	0.16	209.67	0.16	8.95	6.50	140.52	4.20	1105.70	1123.49		PC
LEAR	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
LEAR	DRY	CLEAR	CLEAR	0.28	249.58	0.17	230.32	0.16	6.66	6.00	115.04	4.40	1106.18	1119.28	NOT PUMPING ELEV. 1118	CLEAR
LEAR	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
LEAR	DRY	CLEAR	DITTO	0.31	292.23	0.19	273.66	0.18	8.95	0.51	120.88	4.70	1106.86	1120.63		LT RN
LEAR	DRY	CLEAR	V. ACTIVE	0.32	308.97	0.20	296.31	0.20	11.84	0.53	133.08	5.00	1107.55	1123.47		CLEAR
LEAR	DRY	CLEAR	NORMAL	0.26	222.50	0.14	170.47	0.10	2.06	6.30	84.36	-2.10	1093.90	1124.75		CLDY
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
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 · S-RAVINE W/O MUCH FLOW W/ NO PUMPING	T-STORMS
DRY	DRY	?	SILTY ACT	0.12	87.12	0.10	101.19	0.00	0.00	3.00	20.34	-25.00	1071.00	1124.87		CLDY
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
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
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
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
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
DRY	DRY	DRY	1BOIL	0.10	60.80	N/A	N/A	0.00	0.00	1.90	6.49	-29.80	1066.20	1118.4		CLEAR
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
DRY	DRY	DRY	1BOIL	0.08	35.80	N/A	N/A	0.00	0.00	0.75	0.84	-29.80	1066.20	1118.34		CLEAR
DRY	DRY	DRY	1BOIL	0.02	4.18	N/A	N/A	0.00	0.00	0.00	0.00	-29.80	1066.20	1118.4		CLEAR



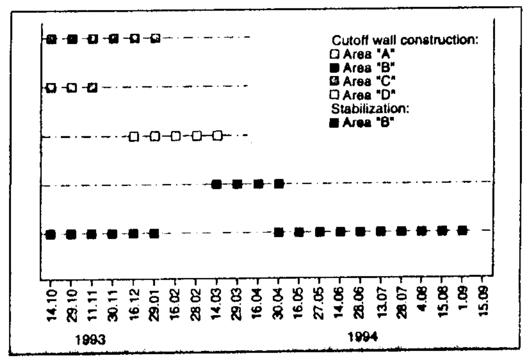




TOP LEFT and LEFT:
Figure 6. Evolution of seepage volumes: Parshall Flumes No1 and No2.

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

RIGHT:
Indicative schedule of cut-off wall contruction. To be referred to in association with Figures 6, 7, 8 and 9.



diameter steel casings were drilled to the level of 'recoverable rock' and cementitious mixes injected during their withdrawal. Totals of 1062m of drilling and 216m^3 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 stabilisation 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 of construction in this area were suspended. After much discussion, a modified grouting-based method was selected, in which the work platform, embankment, overburden, weathered rock, and the top 0.9m to 1.5m 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 813mm 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 stabilisation 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 1124m^3 of grout were injected plus 101m^3 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 4.5m to 27m 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 the 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 3801m^3 of grout and 1952m^3 of downstage concrete were used, both volumes considerably in excess of neat drilled hole volume, emphasising the very cavitated nature of the ground in this area.

The various concrete mixes used during construction were produced by an automatic batching plant in the immediate project area. It was rated at 153m^3/h. Transport to the cut off was by means of 7m^3 truck mixers. Mixes were varied during the work in response to experiences gained, and strong QA/AC 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:

Coarse aggregate	950-90 kg/m^3
Fine aggregate	760-810 kg/m^3
Cement	290-240 kg/m^3
Flyash	60-80 kg/m^3
Water	160-136 litres/m^3
Reducer N	0.4-0.5 kg/m^3
Reducer 1	0.3-0 kg/m^3
Air entraining agent	approx 0.1 kg/m^3
Calcium	0-1.0 kg/m^3

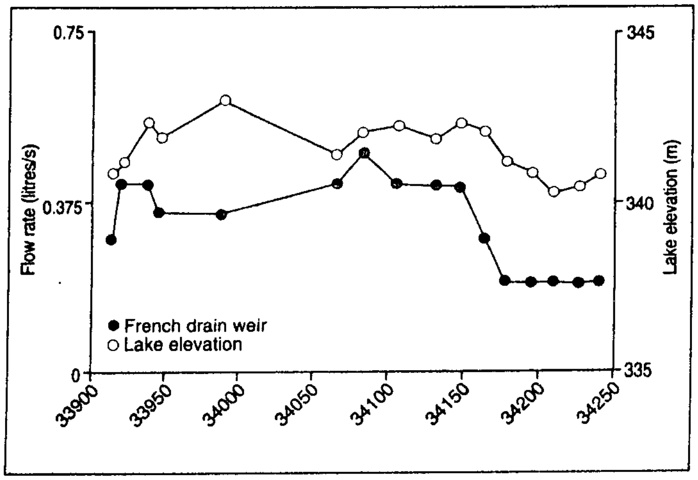
Water was heated or chilled, depending on the other material and ambient, temperatures. Final concrete placement data for cut-off wall construction are shown in **Figure** 5. Total quantities of work conducted are summarised in **Table 2**.

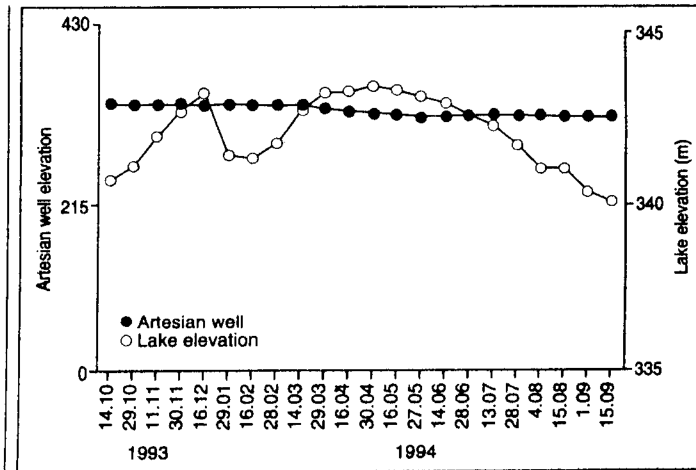
Effectiveness of the cut-off

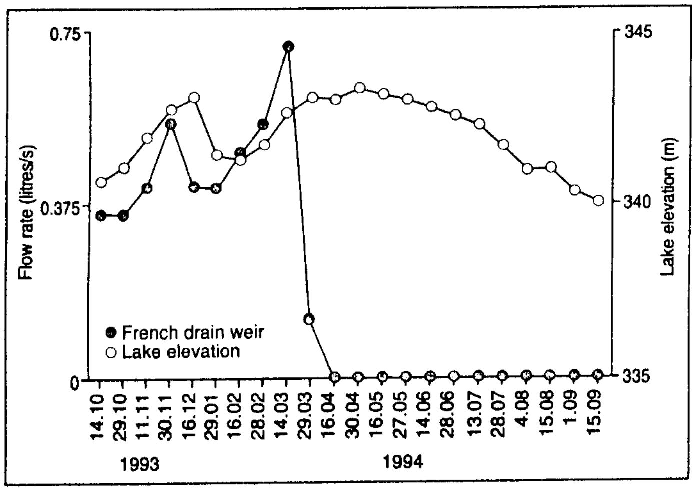
Data was recorded from the existing seepage monitoring instrumentation. Of five seepage areas (SA-1 to SA-5), the area of most concern was SA-1, located in a natural gully 94m downstream of the centreline of dike one at stn 71+00 between elevation 321m and 315m. Besides the piezometric network in the three embankments, specific measuring devices were installed to monitor the seepage exiting downstream of dike one. The most significant of these were:

Seepage area SA-1

Parshall Flume No1:	measures flow from SA-1 (**Figure 6**).
Parshall Flume No2:	measures flow from all the seepages from dike one (Figure 6).
V-notch Weir:	measures surface water seepage from SA-1 (**Figure 7**).







TOP LEFT and LEFT:
Figure 8.
Evolution of seepage volumes: French Drain Weir.

FAR RIGHT TOP:
Figure 9.
Evolution of seepage: Artesian Well.

Seepage area SA-2
French Drain Weir: connects to Parshall Flume No2 (**Figure 8**).
Artesian Well (**Figure 9**).
Actual data are provided in **Table 3**.

Major observations are:

●Parshall Flumes No1 and No2 - 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 stabilisation of area B commenced: flows decreased. By mid-September 1994, after surface pumping had ceased, the remnant seepage was barely 0.3 litres/s, compared to a maximum of over 81 litres/s 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 stabilising at 0.2 litres/s when the level fell below 341m. At the beginning of grout stabilisation 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 0.7 litres/s on March 14, 1994, three days after the completion of area D. However, by the end of March 1994, the flow had dropped to 0.1 litres/s, and eventually dried up totally two weeks later.

●Artesian Well - reacted, with delay to lake level, but showed a 12.6m drop in March 1994, despite the rise in lake level. In mid-June 1994 it dropped to its 'drying up' elevation of 325m.

In general these measurements showed that, prior to construction, the seepage was tens of litres/sec, varying with lake level. In mid-March 1994, when area D was completed and grout stabilisation 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 0.3 litres/s.

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 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.

Acknowledgements

This paper summarises the efforts of a large number of dedicated and motivated people over a long period: to single out specific contributors would risk causing offence to the great majority, through omission. The organisations who share the credit for this project include the US Army Corps of Engineers, Rodio, Nicholson Construction Company, and various major subcontractors, including Keystone Drilling Services Inc, and Beaver Lake Concrete Inc.

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