SEEPAGE REMEDIATION BY POSITIVE CUT-OFF WALLS: A COMPENDIUM AND ANALYSIS OF NORTH AMERICAN CASE HISTORIES

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ABSTRACT

This paper provides, in tabulated and summarized forms, details from a total of 22 North American dams which have been remediated against seepage and the consequences of seepage, by using some form of "positive cut-off." The purpose of the paper is to provide perspective to potential users of the various techniques in relation to such factors as depth capability, geotechnical suitability, constructability, QA/QC and verification, and cost. The technological scope of the paper is limited to projects involving concrete walls ("diaphragm walls") built by panels or secant piles, soilcrete walls built by the Deep Mixing Method, and soil-cement walls. Input is requested from interested readers to expand and modify (as necessary) the information presented herein. The paper assumes a certain level of familiarity with the respective techniques on the part of the reader, and so does not describe their detailed sequential steps of construction.

RÉSUMÉ

Cet article présente un résumé des données provenant de 22 barrages nord-américains sur lesquels ont a utilisé des « parafouilles positifs » pour régler des problèmes de suintement et, par le fait, même éviter ses conséquences néfastes. L'article a comme objectif d'informer les utilisateurs potentiels de ces divers parafouilles sur la profondeur, l'acceptabilité géotechnique, la constructibilité, l'assurance et le contrôle de la qualité (AQ/CQ), la vérification ainsi que les coûts de ces derniers. La portée technologique de cet article ne s'étend qu'aux aménagements disposant de murs en béton (« parois moulées ») construits en palplanche ou en pieux sécants, de murs en béton projeté construits au moyen de la méthode de malaxage en profondeur et de murs sol-ciment. L'intervention des lecteurs intéressés à développer et modifier (si nécessaire) l'information présentée ici est la bienvenue. Comme cet article tient pour acquis que le lecteur est familier avec les techniques présentées, les différentes étapes de construction de ces techniques ne seront pas décrites en détails.

1. SCOPE OF STUDY

For over 30 years, major dams in North America have been remediated against the consequences of reservoir leakage by the installation of some form of "positive cut-off." Such cut-offs have been successful in eliminating (or greatly minimizing) seepage through embankments (and dikes) at their contacts with permeable bedrock, and within the bedrock itself. The actual *quantity* of water lost is, per se, rarely the major issue at hand. Rather, the critical factor is usually the *effect of the movement* of water in terms of its ability to cause piping and erosion of dam and foundation materials which leads in turn to the potential for causing potentially catastrophic events. The manifestations of such mechanisms are well known: structural movements from minor depressions to major sinkholes; increased flow from drains and wells; disturbing trends from dam and foundation piezometers; and the presence of sediment or embankment materials in springs or seepage points on or below the dam.

Such events may lead to the conclusion that the dam in question has a serious dam safety problem, and/or that a sudden and uncontrolled loss of reservoir may occur unless remediation is conducted. Major seepage problems are often recognized as early as first filling of the dam, when they are typically associated with some form of construction (or design) defect in the embankment itself, or at its contact with the rock of the abutments or foundation. On the other hand, it may take much longer — tens of years — for the problem to manifest itself if the seepage is causing slow and progressive erosion of foundation material, such as the residual clay infill of heavily karstified terrains. It is also often the case that a truly definitive remediation measure is not selected — often for short-term financial reasons — when the decision to remediate is first actually made. For example, the use of drainage ditches, and blankets, berms, or "traditional" grouting methods in karst, has been found to be only partially and/or temporarily effective, as the situation continues to deteriorate.

The authors have long been involved in the design and construction of major remedial cut-offs, both in North America and elsewhere. Such cut-offs require a very high degree of skills and knowledge on the part of the specialty contractors involved: no project is ever completely "straightforward," and the majority is anything but. Furthermore, these works are usually conducted in an atmosphere of high anxiety (particularly on the part of the owners) and intensity, and are typically of significant scale. The authors note, however, that the majority of owners and designers contemplating such projects rarely have — or have time to acquire — an accurate perspective of precedent practice, in general, and of scale and constructability issues in particular. A recent inquiry (quite serious) was received regarding the potential for the installation of a cut-off thousands of feet long and 800 feet deep through a dam overlying a soluble and erodible rock foundation. Despite a wealth of historical and technical input from industry specialists throughout the world, the owner clings to the seduction that such a structure is practically feasible and economically viable.

This paper presents a summary of data published relating to major North American seepage remediations. It provides, in tabular form, salient details relating to the nature of the ground and the construction details of particular interest and relevance. A total of 22 case histories are presented: readers are warmly invited to contribute their own information to this database, and to provide information on case histories not covered. The population of case histories divides itself into two lists:

- "The A List" – case histories with relatively comprehensive published data.
- "The B List" – case histories about which little or no data have been published or found (so far 8 other projects).

The authors would hope that, with time, the former list can be expanded at the expense of the latter.

The scope of this review has had to be carefully (if arbitrarily) circumscribed. The authors have included only concrete and plastic concrete walls (by secant pile, clamshell grab, or hydromill*), cement-bentonite walls, soil-cement-bentonite walls, and cut-offs created by the Deep Mixing Methods (Bruce, 2000-2001). Remedial cut-offs created by grouting, sheet piles or other such technologies are deemed beyond the current scope. Space also prevents a recitation, for each case history, of the events and observations leading to the decision to actually conduct such a remediation. The interested reader is referred to the relevant publications, which are often in any case, "top heavy" with such analytical and diagnostic information. Space also prohibits a detailed exposition of the technological aspects of the various construction methods, and it is assumed that the reader has working knowledge of the details of the respective construction methods.

As a final introductory point, it is clear (and understandable) that the technical papers which form the data pool for this paper are most often written within a very short time of the completion of the remediation. Little information therefore exists on the longer-term performance of such cut-offs — such papers are not very eye-catching to the casual reader, no matter how fundamental they may be to the specialists. There is therefore a tendency to assume that, in the absence of evidence to the contrary, these diaphragms do in fact continue to function as efficiently as they did upon construction. This is not necessarily a valid assumption nor a universal truth. There is evidence that even a properly functioning cut-off may be bypassed by water flowing under or around it, if the geological conditions so permit. For example, at W.F. George Dam, AL, two prior cut-off walls had not obviated the necessity to install the third (Case History 20, Table 1), while at Wolf Creek Dam, KY, a more extensive cut-off is currently being contemplated to arrest seepage which has apparently developed below and around the existing cut-off (Case History 1, Table 1). This long-term degradation has been referred to being "like a relentless and indefatigable siege army, incessantly trying to find a weakness to exploit" (Ressi, 2006). Again, the authors challenge their colleagues to reappraise the long-term performance of these walls, and to publish the results.

2. THE CASE HISTORIES REVIEWED

Tables 1 and 2 list the projects which the authors have reviewed in the preparation of this paper.

Table 2. Names of 8 dams known to have been remediated with cutoffs but for which details have not yet been found.

- ARKANSAS ELECTRIC DAM 2, AR (Cutoff and structural walls completed in 1996. Consultant URS Woodward Clyde, Contractor: Soletanche.)
- W.F. GEORGE, AL (First stage remediation under embankments, 1981-1985).
- HODGES VILLAGE DAM, MA (Built in 1959).
- SAM RAYBURN DAM, Jasper, TX (USACE structure remediated with soil-cement backfill pre-1997).
- STEWARTS BRIDGE DAM, NY (Plastic concrete cut-off, built by clamshell. Contractor: ICOS. Early 1990's.)
- WATERBURY DAM, VT (Built in 1938).
- WHITNEY POINT DAM, NY (Built in 1942).
- WEST HILL DAM, MA (USACE Structure, built in 1961, 140,000 sf of concrete wall created through core, and boulders into bedrock. Trial sections in October 2001, production March-July 2002, Contractor: Soletanche.)

* There are at least 3 European companies which build such machines. Each refers to the machine by a different trade name, e.g., hydrofraise, fresa, cutter. To avoid confusion, the authors have standardized on the term "hydromill."

Table 1. Details of remedial dam cutoff projects which are well described ("A List").

Dam Name and Year of Remed-iation	Contractor	Type of Wall	Composition of Wall	Ground Conditions	Purpose of Wall	Scope of Project				References
						Area	Width	Depth	Length	
1. WOLF CREEK, KY. 1974-1978	ICOS	24-inch diameter Primary Piles, joined by 24-inch wide clamshell panels. Two phases.	Concrete.	Dam FILL, and ALLUVIUM over argillaceous and karstic LIMESTONE with cavities, often clay-filled.	To provide a "Positive concrete cut-off" through dam and into bedrock to stop seepage, progressively developing in the karst.	270,000 sf (Phase 1) plus 261,000 sf (Phase 2)	24 in	Max. 280 ft	2,000 ft plus 1,250 ft	• ICOS brochures (undated) • Fetzer (1988)
2. ADDICKS AND BARKER, TX. Completed in 1982 (Phase 1 took 5 months)	Soletanche*	36-inch thick panel wall with clamshell excavation using Kelly	Soil-Bentonite.	Dam FILL over CLAY	To prevent seepage and piping through core.	450,000 sf (Phase 1) plus 730,000 sf (Phase 2)	36 in	Max 66 ft typically 35 to 52 ft	8,330 ft plus 12,900 ft	• Soletanche website.
3. ST. STEPHENS, SC. 1984	Soletanche	24-inch-thick concrete panel wall, installed by Hydromill. Plus upstream joint protection by soil-bentonite panels.	Concrete and soil-bentonite.	Dam FILL, over sandy marly SHALE.	To provide a cut-off through dam.	78,600 sf (concrete) plus 28,000 sf (soil-bentonite)	24 in	Max. 120 ft including 3 ft into shale	695 ft	• USACE Report (1984) • Soletanche (various) • Parkinson (1986) • Bruce et al. (1989)
4. FONTENELLE, WY. 1986-1988	Soletanche	24-inch-thick concrete panel wall installed by Hydromill. Minor soil-bentonite panels.	Concrete and soil-bentonite.	Dam FILL over horizontally bedded SANDSTONE.	To prevent piping of core into permeable sandstone abutment.	50,000 sf (LA test) plus 100,000 sf (RA test) plus 700,000 sf (Prod-uction)	24 in	Max 180 ft including 16 to 160 ft into rock	Approx. 6,000 ft	• Cyganiewicz (1988) • Soletanche (various)

* Soletanche have operated in the U.S. under different business identities over the years. "Soletanche" is used herein as the general term.

Dam Name and Year of Remed-iation	Contractor	Type of Wall	Composition of Wall	Ground Conditions	Purpose of Wall	Scope of Project				References
						Area	Width	Depth	Length	
5. NAVAJO, NM. 1987-1988	Soletanche	39-inch-thick panel wall installed by Hydromill.	Concrete.	Dam FILL over flat-lying SANDSTONE with layers of SILTSTONE and SHALES. Very fractured, weathered and permeable with vertical and horizontal joints.	To prevent piping of core into permeable sandstone abutment.	130,000 sf	39 in	Max 400 ft including over 50 ft into rock	450 ft	• Davidson (1990) • Dewey (1988)
6. JACKSON LAKE, WY. 1987-1988	Geo-Con using Seiko equipment	34-inch-thick deep mixed wall.	Soilcrete.	ALLUVIUM, comprising mainly sands, but with interbedded coarse gravels and other materials.	To provide seepage cut-off through variable, but generally permeable alluvials under reconstructed dam.	248,312 sf	34 in	Max 100 ft, average 62 ft	3,985 ft	• Farrar et al. (1990)
7. PROSPER-TOWN, NJ. Late 1988 (Less than 1 month)	Franki	“Conventional” cement-bentonite wall using backhoe.	Cement-bentonite.	Dam FILL, relatively permeable sand and silt, and ALLUVIALS over impermeable GLAUCONI-TIC CLAY	To prevent seepage through fill and alluvials	14,000 sf	32 in	15 to 33 ft (average 24 ft)	475 ft	• Khoury et al. (1989)

Dam Name and Year of Remediation	Contractor	Type of Wall	Composition of Wall	Ground Conditions	Purpose of Wall	Scope of Project				References
						Area	Width	Depth	Length	
8. MUD MOUNTAIN, WA. 1988-1990, (Mainly over period December 1989 to April 1990)	Soletanche	33- and 39-inch-thick panels wall installed by Hydromill. Extensive pregrouting of core.	Concrete.	Dam FILL silty and sandy, over very hard, blocky cemented ANDESITE (UCS over 20,000 psi)	To prevent seepage through the core	133,000 sf	33 in in abutments, 39 in in center	Max. 402 ft	700 ft	• Soletanche brochures • Eckerlin (1993) • ENR (1990) • Davidson et al. (1991) • Graybeal and Levallois (1991)
9. BACK CREEK, MD. 1990	Unknown	30-inch wide backhoe wall	Cement-Bentonite.	Dam FILL over fine SANDS and SILTS	To prevent seepage through dam adjacent to culvert and below tree roots.	814 sf	30 in	11 ft	74 ft	• Hillis and Van Aller (1992)
10. WISTER, OK. 1990-1991 (6 months)	Bauer	24-inch-thick panel wall installed by Hydromill.	Plastic concrete.	Dam FILL, over 30 feet of ALLUVIALS overlying SANDSTONE and SHALE	To prevent piping through the embankment.	216,000 sf	24 in	Approx. 54 ft	Approx. 4,000 ft	• Erwin (1994) • Erwin and Glenn (1991)
11. WELLS, WA. 1990-1991 (7 months, 208 working shifts)	Bencor-Petrifond	30-inch-thick panel wall installed by clamshell and joint pipe ends.	Concrete.	Dam FILL with permeable zones over miscellaneous ALLUVIUM and very dense TILL.	Prevent piping through permeable core materials, in gap between original cutoff and rockhead.	124,320 sf	30 in	80 to 223 ft	849 ft	• Kulesza et al. (1994) • Roberts and Ho (1991)

Dam Name and Year of Remed-iation	Contractor	Type of Wall	Composition of Wall	Ground Conditions	Purpose of Wall	Scope of Project				References
						Area	Width	Depth	Length	
12. CUSHMAN, WA. 1990-1991 (4 months)	SMW Seiko	24-inch wide DMM wall formed with 40-inch triple augers	Soilcrete.	Dam FILL over variable glacial deposits (OUTWASH, LACUSTRINE and TILL), often dense with boulders.	In two sections adjacent to Spillway to arrest seepage.	39,420 ft	24 in	Max 140 ft, average 103 ft	383 ft	• Yang and Takeshima (1994)
13. BEAVER, AR. 1992-1994 (22 months)	Rodio-Nicholson	24-inch-thick wall created by 34-inch secant columns at 24-inch centers.	Concrete.	Dam FILL over very variable and permeable karstic LIMESTONE with open and clay-filled cavities. Some sandstone.	To prevent seepage through karstic limestone under embankment.	207,700 sf	24 in	80 to 185 ft	1,475 ft	• Bruce and Dugnani (1996) • Bruce and Stefani (1996)
14. LOCKING-TON, OH. 1993 (25 working days)	Geo-Con	24-inch-thick Deep Mix Wall created with 36-inch shafts.	Soilcrete.	Non-homogen-eous hydraulic dam FILL.	To prevent seepage through upper part of embankment dam	66,603 sf	24 in	8 to 21 ft	4,415 ft	• Rinehart and Berger (1994) • Walker (1994)
15. MEEK'S CABIN, WY. 1993	Bauer	36-inch-thick panel wall formed by Hydromill.	Plastic concrete.	Dam FILL over very variable glacial TILL and OUTWASH comprising sand, gravel, cobbles, and boulders.	To prevent seepage through glacial outwash deposits.	125,000 sf	36 in	130 to 170 ft including minimum 10 ft into lower glacial till	825 ft	• Pagano and Pache (1995) • Gagliardi and Routh (1993)

Dam Name and Year of Remed-iation	Contractor	Type of Wall	Composition of Wall	Ground Conditions	Purpose of Wall	Scope of Project				References
						Area	Width	Depth	Length	
16. McALPINE LOCKS AND DAM, KY. 1994 (6 months)	ICOS	24-inch panel wall formed by clamshell and chisel. Upper portion pretrenched with backhoe and filled with cement-bentonite.	Concrete.	Very variable FILL, with rubble, cobbles, and boulders over silty CLAY over SHALE and LIMESTONE.	To prevent seepage through dike and alluvials.	51,000 sf	24 in	30 to 90 ft plus 5 ft into bedrock	850 ft	• Murray (1994)
17. TWIN BUTTES, TX. 1996-1999	Granite-Bencor-Petrifond	30-inch wide wall formed with panel methods (Kelly and cable suspended grabs, plus chisels.) Hydromill also used.	Soil-cement-bentonite	Dam FILL over CLAY and ALLUVIAL gravel often highly cemented (up to 15,000 psi) and SHALEY SAND-STONE bedrock.	To prevent seepage through dam foundation causing uplift or blowout	1,400,000 sf	30 in	Max 100 ft deep including at least 2.5 ft into rock	21,000 ft	• Dinneen and Sheshkier (1997)
18. LEWISTON LEVEE, WA. 2001 (2 weeks)	Raito	Deep Mixed Wall formed by multi-axis machine.	Soilcrete.	Levee FILL and ALLUVIALS, generally soft but with dense gravel layer and boulders.	To prevent seepage through levee.	15,000 sf (est)	39 in (est)	30 ft	500 ft	• Gibbons and Buechel (to be defined_)
19. CLEVELAND, BC. 2001-2002 (4 months)	Petrifond and Vancouver Pile Driving	32-inch panel wall constructed by cable suspended clamshell.	Plastic Concrete.	Hetero-geneous glacial sediments including SILT, SAND, GRAVEL and TILL with hard igneous boulders.	To prevent seepage through glacial and interglacial foundation sediments, especially 20-foot sand layer.	55,000 sf (est)	32 in	20 to 75 ft	1,004 ft	• Singh et al. (2005)

Dam Name and Year of Remed-iation	Contractor	Type of Wall	Composition of Wall	Ground Conditions	Purpose of Wall	Scope of Project				References
						Area	Width	Depth	Length	
20. W.F. GEORGE, AL. 2001-2003	Treviicos-Rodio	24-inch-thick secant pile wall (50-inch diameter at 33-inch centers) plus hydromill through concrete structures.	Concrete.	Over 90 feet of water over LIMESTONE with light karst, and very soft horizons (rock strength over 14,000 psi in place).	To prevent seepage through karstified bedrock under concrete dam section.	Approx. 300,000 sf including hydromill wall (50,000 sf)	24 in	100 ft of excavation (under 90 ft water)	2,040 ft	• Ressi (2003) • Ressi (2005)
21. MISSISSINEWA, IN. 2002-2005 (including shutdown for grouting)	Bencor-Petrifond	18-inch thick panel wall, using 30-inch hydromill, with clamshells through dam.	Concrete.	Dam FILL over karstic LIMESTONE (to 25,000 psi), very permeable and jointed.	To prevent piping into karstic limestone foundation.	Approx. 460,000 sf	30 in	148 to 230 ft (including max 148 ft into limestone) av. 180 ft.	2,600 ft	• Hornbeck and Henn (2001) • Henn and Brosi (2005)
22. TAYLORSVILLE, OH. 2004 (22 days)	Brayman	30-inch-thick cut-off installed by backhoe.	Self-hardening cement-bentonite.	Dam FILL, clayey.	To prevent seepage through the core.	Approx. 80,000 sf	30 in (est)	28-40 ft	2,400 ft	• Fisher et al. (2005)

3. KEY POINTS: “LESSONS LEARNED”

For each of the projects listed in Table 1, the most interesting observations and conclusions are summarized below. For brevity, they are listed in bullet form.

1. WOLF CREEK, KY (1974-1978)

- Largest man-made reservoir east of the Mississippi river.
- First major dam rehabilitation of its type, method selection (Figure 1) driven by necessity to keep lake level high, and precedent success with “new” wall of similar type at Manicouagan Dam, Quebec (maximum depth 400 feet). Contractor procured by “Corps Two Step” RFI process.

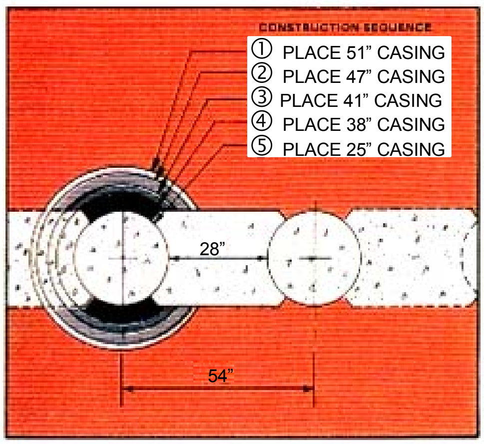

Figure 1. Wall Configuration in Plan, Wolf Creek Dam, KY (ICOS Brochure, Undated)

- Critical Primary holes had to be drilled with reverse circulation to a 1/560 tolerance in any direction. This required 60 “painstaking” construction steps. Verticality checked at 30-foot intervals.
- Data from verticality checks were as follows:

PHASE	PRIMARY PILES	DEVIATION MEASURED	NUMBER	CUMULATIVE %
1	221 Nr.	0-3 inches	82	87
		0-4 inches	144	65
		0-5 inches	184	83
		0-6 inches	213	96
		Only 8 piles had over 6 inch deviation, 4 for “specific cause”		
2	278 Nr.	0-3 inches	122	44
		0-4 inches	200	72
		0-5 inches	257	92
		0-6 inches	277	99.7
		Only 1 pile was out of tolerance		

- Wall had to penetrate in places at least 2 feet into existing concrete structures having a slope of 1 in 10.
- Phase 2 involved drilling through about 100 feet of karstic limestone.

2. ADDICKS AND BARKER DAMS, TX

- Huge project by contemporary standards, costing $15 million at the time.
- Two consecutive phases of work using kelly-mounted clamshell.

3. ST. STEPHENS, SC (1984)

- First use of Hydromill technology for dam remediation in the U.S., as opposed to use of clamshells and joint pipes, or secant piles and/or panels.
- Savannah District of USACE had just designed two such “new” walls at the Clemson Diversion Dams. Therefore they had confidence in a concrete remedial wall installed in panels, as opposed to the “traditional” soil-bentonite wall. Concrete designed to be over 3000 psi (to resist erosion).
- Primary and Secondary panels were 30 feet and 7 feet long, respectively.
- Due to seismic concerns, each panel joint was backed up by an upstream 38-foot-long soil-bentonite panel, as was concrete/embankment interface (Figure 2).
- Very prescriptive slurry and concrete specifications, and intense instrumentation of performance.
- Estimated that wall production would take 180 days (at 5 days/week) and cost around $2.6 million.
- Hydromill became stuck in trench within a few minutes of the slurry reverse circulation pumps being shut off. Retrieval took several days of flushing and cleaning the bentonite slurry.

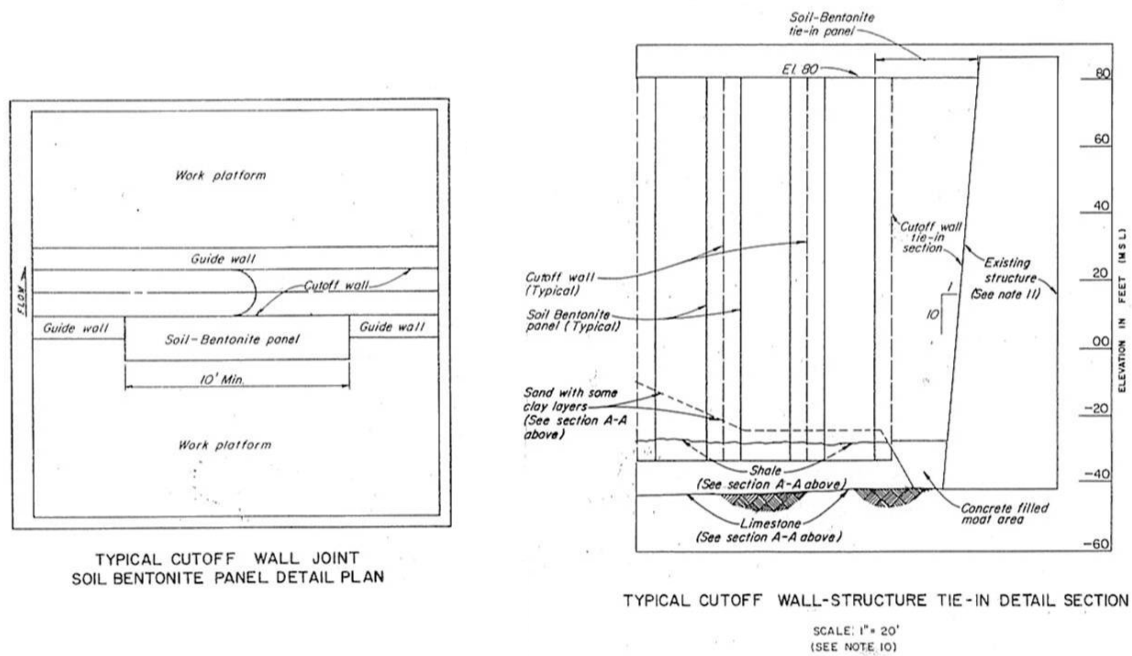

Figure 2. Typical Cut-off Wall Joint and Soil Bentonite Panel Detail Plan, St. Stephens Dam, SC (USACE, 1984).

4. FONTENELLE, WY (1986-1988)

- Two major full scale field tests at the abutments preceded production.
- Construction complicated by existence of three concrete structures in the dam, requiring plugging (with concrete) and deviation of the wall.
- Grouting and soil-bentonite walls used to assure adequate hydraulic seals at certain contact zones between concrete and embankment structures (Figure 3).

5. NAVAJO, NM (1987-1988)

- Deepest remedial wall when constructed (400 feet).
- Primary and Secondary panels were 19 feet long and 7 feet long, respectively.
- Contractor conducted special full scale test in France in December, 1986. Several panels 30 inches wide x 7 feet long x 400 feet deep were successfully installed. Verticality was measured by two methods – in real time, and for verification (KODEN) before concreting. Results indicated about 0.1% deviation at depth.
- Production encountered five major slurry losses, the largest being over 500 cubic yards of slurry plus 100 cubic yards of sediment at 300 feet depth (slurry never seen). Second largest was almost 200 cubic yards of slurry plus 50 cubic yards of sand – exited 400 feet away in the dam’s “groin”.
- Very difficult excavation into steep valley required (Figure 4).
- Very intense array of instrumentation to measure effect on dam during and after construction.
- Later coring of wall indicated fissuring of concrete and, arguably, an air of disappointment (Davidson, 1990).

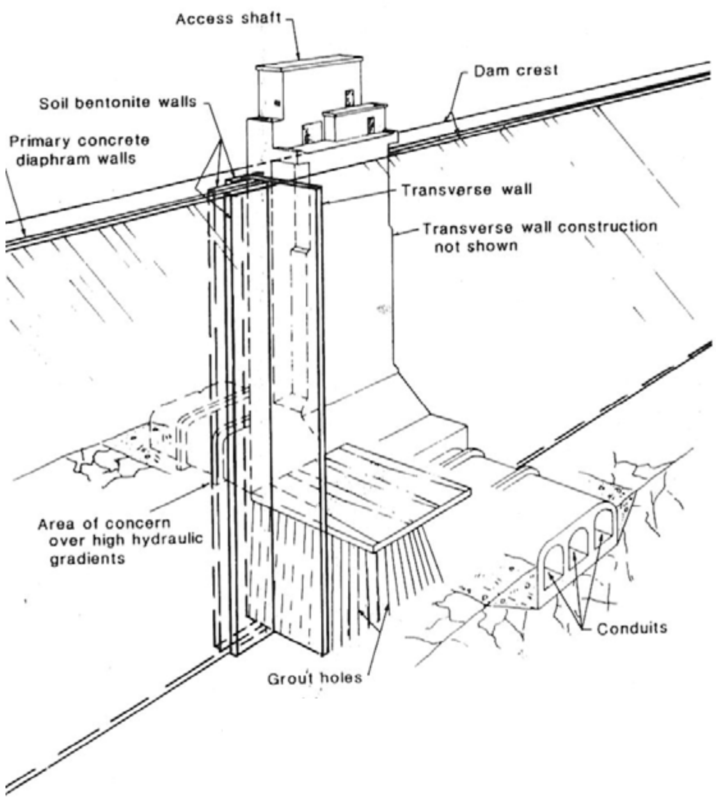

Figure 3. Wall Construction at Fontenelle Dam Outlet Works (Cyganiewiez, 1988).

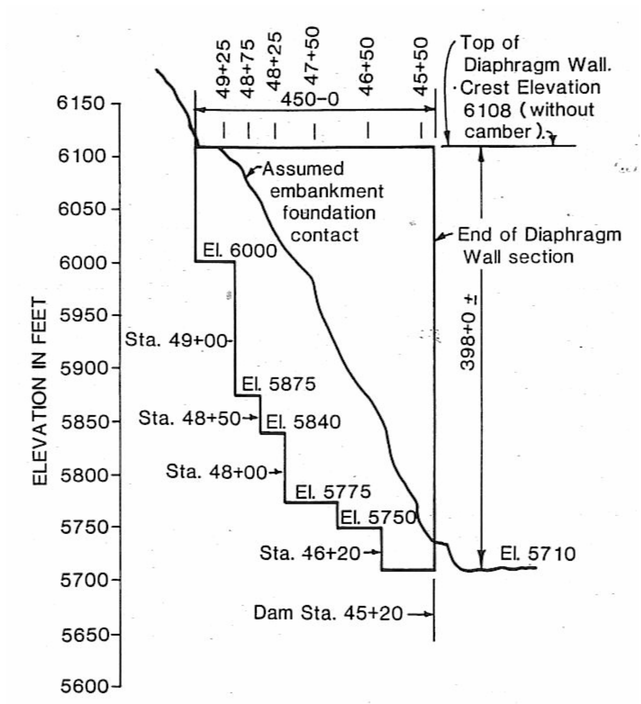

Figure 4. Navajo Dam – Profile of left abutment concrete diaphragm wall (Dewey, 1988).

6. JACKSON LAKE, WY (1987-1988)

- First U.S. use of Deep Mixing Method (DMM) for dam rehabilitation – offered as a new technology alternative.
- DMM used for seismic mitigation, as well as to provide seepage cutoff in alluvials in the foundation of an existing dam, previously demolished.
- Excellent QA/QC and verification data obtained and published: this encouraged future use for other applications, as did widespread promotion by the contractors involved.

7. PROSPERTOWN, NJ (1988)

- Cement-bentonite wall had target permeability of 10^{-6} cm/s and comprised (for each batch) 5.7 cubic yards of Bentonite-Water slurry, 4.5 gallons of fluidifier plus 3200 lbs of cement. This permeability was judged a difficult target to achieve and a practical recommendation was 5×10^{-6} cm/s.
- Reservoir lowered before construction began.
- Minimum of 2-foot "key-in" into each previous day's work to assure fresh contact.
- Cement-bentonite slurry decreased in permeability by a factor of 3 between 5 and 28 days of curing.

8. MUD MOUNTAIN, WA (1988-1989)

- New generation of Hydromill (after Navajo Dam project) required to combat rock hardness and very steep valley profile (Figure 5).

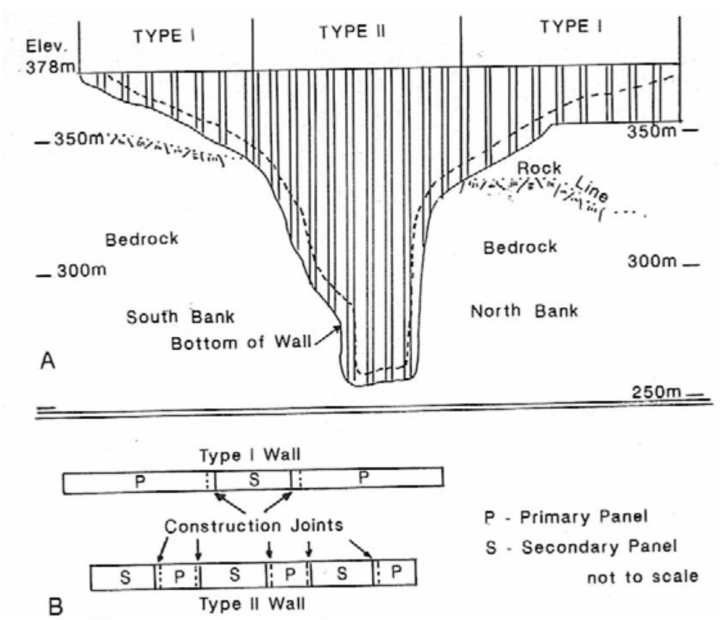

Figure 5. Mud Mountain Dam, WA
A. Cut-off wall profile (view looking downstream) B. Cut-off wall layout plan.
Dashed lines show location of vertical concrete construction joint (Eckerlin, 1993).

- About 5000 cubic yards of slurry lost due to hydraulic fracturing in initial panels (over 900 cubic yards in one, within a few minutes), requiring intense 3-row grout curtain in core (20,000 linear feet of drilling and 4500 cubic yards of grout, void fill and claquage). Core was cracked.
- Thereafter, panel width limited to 9 feet and panel overlap increased to 14 inches as additional safety measures.
- 15 of 57 panels reached depths over 330 feet, and two had to cut over 170 feet into andesite. World record for depth of remedial cut-off through an embankment dam set on January 31, 1990 (403 ft).
- Continuous real time instrumentation indicated longitudinal deviations of less than 4 inches and relative lateral deviations less than 8 inches at depth.
- Concrete of Primary panels was color-coded to confirm acceptable overlap with Secondaries.
- Initial contract about \$20 million, final cost just under \$24 million.

9. BACK CREEK DAM, MD (1990)

- Very small project, but excellent description of cement-bentonite mix design and performance.
- Unit cost of wall about $220/cubic yard (i.e., about $20,000 total).

10. WISTER, OK (1990-1991)

- Previous remedial work (1949) created cracking in crest during grouting, and there were windows in sheet piles.
- Installed from a berm 110 feet upstream of the centerline for cost and temporary dam safety reasons.
- Plastic concrete wall installed 5 feet into rock. 90-day strength 500 to 1000 psi. Total of 326 panels.
- Value of wall $2.89 million. Typical production rate: 1300 ft^2/day.
- Primary panels 18 feet long, separated by 6.56 feet (each hydromill bite was 7.2 feet long).
- Pre-excavation conducted to about 15 feet, and shallow panels (< 15 feet) were excavated by backhoe.

11. WELLS, WA (1990-1991)

- Very good example of intensive, focused site investigation and assessment, before and after wall installation.
- Conducted under full reservoir conditions in 8-month period, with no embedment required in rock.
- Believed to be deepest such wall conducted with conventional clamshell and joint pipe.
- Strict safety measures as to number of panels allowed to be open simultaneously (4); their width (12 feet), their strength at adjacent excavation (700 psi); and bentonite level (maximum 2 feet from crest).
- Grouting conducted as an exploration tool, and anticipated as a remediation if fracturing occurred.
- Only one significant slurry loss (about 900 cubic feet) occurred, resolved by methyl-cellulose additive, 2 bales of straw, 35 bags of dry bentonite, and backfill material ("the situation was expeditiously corrected").
- Price was $45/$ft^2$.

12. CUSHMAN, WA (1990-1991)

- DMM wall conducted to considerable depth (140 feet) and through very difficult and bouldery glacial materials. Predrilling used to facilitate triple auger penetration, and "by pass sections" were installed around certain large boulders.
- Soilcrete had average UCS of over 300 psi, and permeability about 1×10^{-6} cm/s (both very variable).
- Mix design verified in full scale test section, excavated for inspection.
- During construction, holes constantly topped up with soil or soil-grout slurry to maintain borehole stability, prevent sloughing of loose soils, and create a protective filter zone.

13. BEAVER, AR (1992-1994)

- Secant pile method (with down-the-hole hammer (DTH)) selected after initial method (hydromill) could not cut the rock. Total of 738 production piles were installed (Figure 6).
- Drilling in rock conducted through 48-inch-wide concrete wall previously excavated through the embankment (4,713 $yards^2$).
- Pregrouting and downstage techniques were locally required due to particularly unstable ground conditions in certain stretches of the cutoff.
- Close attention to verticality meant that only 24 additional ("conforming") piles were required to assure minimum overlap requirements.
- Secondaries started only when concrete in Primaries exceeded 2000 psi.
- Verification of performance very comprehensive, including flow reduction from over 500 gpm to less than 4 gpm.

14. LOCKINGTON, OH (1993)

- DMM selected as opposed to cement-bentonite wall since remote mixing of backfill could be avoided.
- Jet grouting used to close gap between concrete spillway walls and the DMM cut-off.
- Permeability 3.5×10^{-6} cm/s to 5.4×10^{-8} cm/s, and 7-day UCS varied 6.2 to 48.1 psi. Weight of rig exceeded crest capacity, and large mats were needed. Also grout froze in one mixing shaft causing structural damage to it.

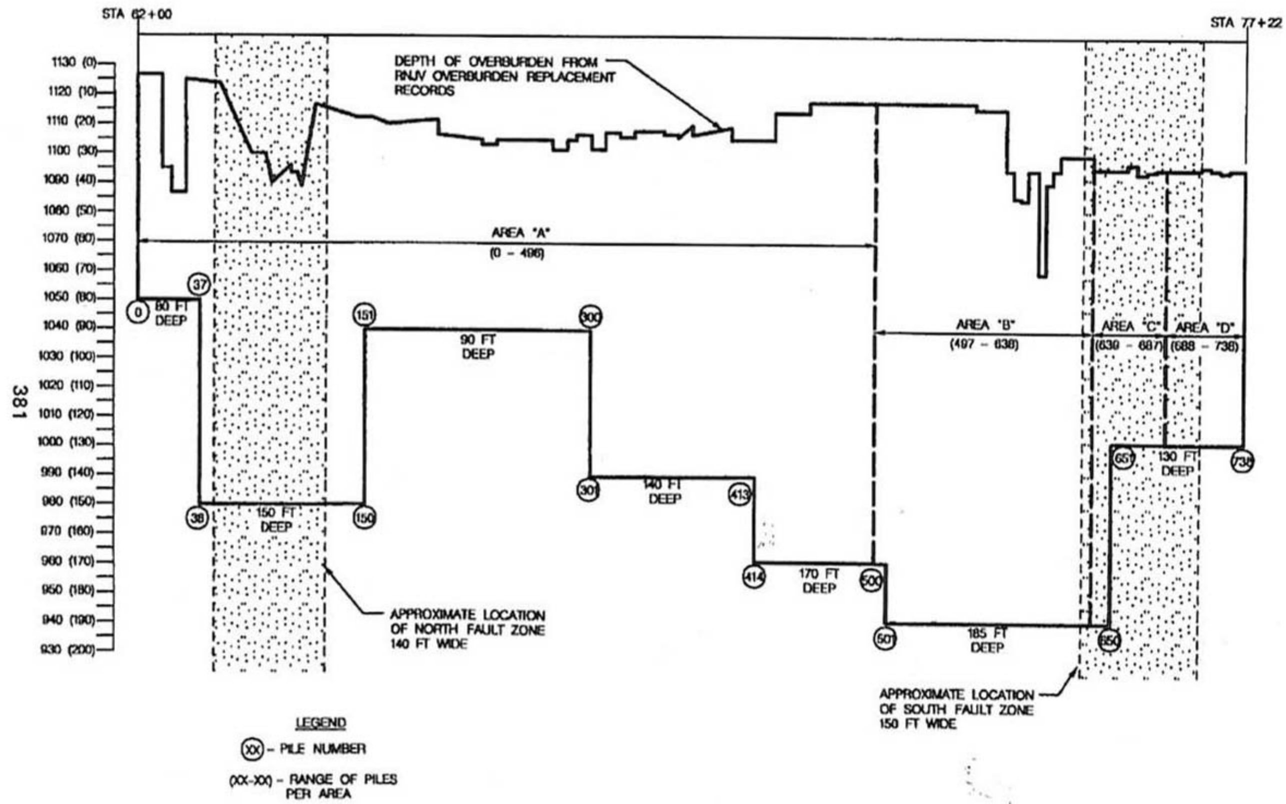

Figure 6. Elevation of the cut-off wall showing main construction parameters. Beaver Dam, AR. (Bruce and Dugnani, 1996).

15. MEEK'S CABIN, WY (1993)

- Very challenging project for several reasons
  - Working platform and surrounding site was limited.
  - Site was remote.
  - Limited construction season (April-September).
  - Excavation through very difficult alluvials and glacials with boulders as big as 42 inches and as strong as 40,000 psi.
  - Contractor developed special roller bit cutter wheels to mount on the hydromill.
  - Plastic concrete target was 400 psi strength and 2.4×10^{-6} cm/s permeability.
- As a backup, traditional cable grab and chisel was planned to deal with excessive boulders. Eventually a powerful hydraulic grab was used to excavate upper dam materials, and the mill used to cut the lower parts. Large boulders extracted by hydraulic grab. Maximum 30-foot-long panels.
- Strong contingencies against slurry loss (4 different principles were deployed).
- Estimated cost $5 million.

16. McALPINE LOCKS AND DAM, KY (1994)

- Pretrenching with backhoe (and backfilling with cement-bentonite) conducted to remove boulders and obstructions and to arrest water movement. Lean mix concrete used to combat voids and large slurry losses.
- Wall had to "eat" into sloping concrete surface (Figure 7).
- Estimated price for the 31 panels was $3.7 million, and the bid price $2.7 million.
- "This type of remediation involving many construction uncertainties and requiring specialized contractor experience should only be contracted through an RFP type solicitation where price is only a portion of the evaluation process."

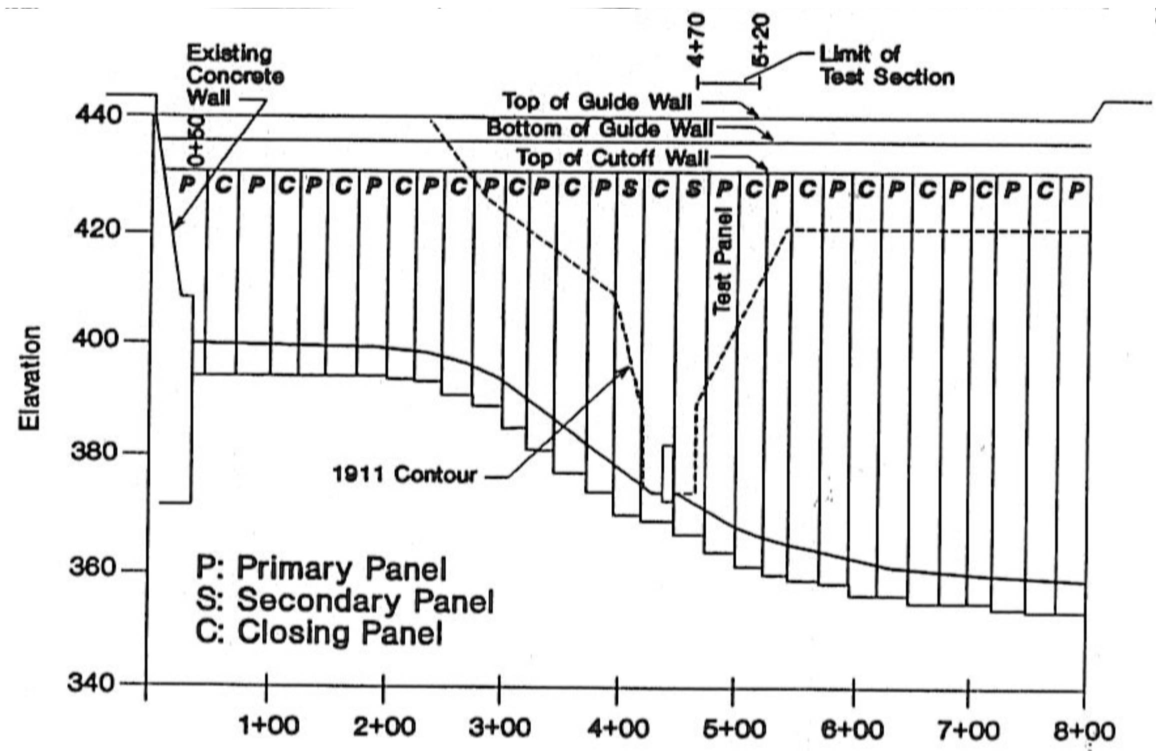

Figure 7. Wall Profile, McAlpine Locks and Dam, KY, (Murray 1994).

17. TWIN BUTTES, TX (1996-1999)

- Longest and largest (in terms of area) dam remedial cutoff yet constructed in North America.
- Excellent example of investigation, design and decision making with respect to choice of wall type and materials (soil-cement-bentonite).
- Very difficult alluvial materials and extreme lateral and vertical variability required chiseling and hydromill.
- Instructive 1200-foot-long test section.
- Backfill target UCS was 100 psi (twice gradient acting on the wall) and permeability was 1 x 10^{-6} cm/s.
- Limited experience with soil-cement-backfill compensated by excellent analysis and research.
- Whole alignment precored at maximum of 100-foot centers to assure adequate toe-in into low permeability bedrock.
- Primary and Secondary panels 50 feet and 8 feet long, respectively.

18. LEWISTON LEVEE, WA (2001)

- DMM favored since soil-bentonite wall was ruled out due to limited access and mixing areas, potential for spillage into river, and short-term stability of the levee.
- Binder comprised cement (220 kg/m^3) and bentonite (80 kg/m^3) to provide soilcrete of minimum 28-day strength of 20 psi and K = 5 x 10^{-7} cm/s. Suitability verified in 20-foot test section.
- Boulders, cobbles and gravels posed penetration problems.

19. CLEVELAND, BC (2001-2002)

- Very detailed case history describing site investigations and assessment, and construction details.
- Wall built in 50 panels, 10 to 29 feet long, penetrating 13 feet into a silt aquitard.
- Plastic concrete 1 to 3 x 10^{-6} cm/s (field) and over 150 psi at 28 days.
- Dewatering system used to maintain g.w. level ≥ 23 inches below slurry level, during winter drawdown.
- A 33-inch-wide "rectifying tool" was passed through each panel prior to placing the concrete.
- Slurry loss into reservoir combated by using lean concrete backfill and limiting panel lengths locally to 10 feet.

20. W.F. GEORGE, AL (2001-2003)

- Whole alignment predrilled and pregrouted to explore in situ conditions and to fill existing voids.
- Wall installed by using reverse circulation pile top rotary rigs through 90 feet of lake water and afterwards connected laterally to existing concrete dam section (Figure 8).
- Hydromill used to continue wall through concrete, sloping "nose" of lock and underwater retaining wall (212 feet deep and 240 feet long).
- Slurry wall had been conducted in 1981-1985 using conventional panel methods through the embankment (2 phases totaling $11.5 million).
- Great technical and logistical challenges and sophistications accommodated by very active Partnering and VECP processes. Estimated cost over $40 million.

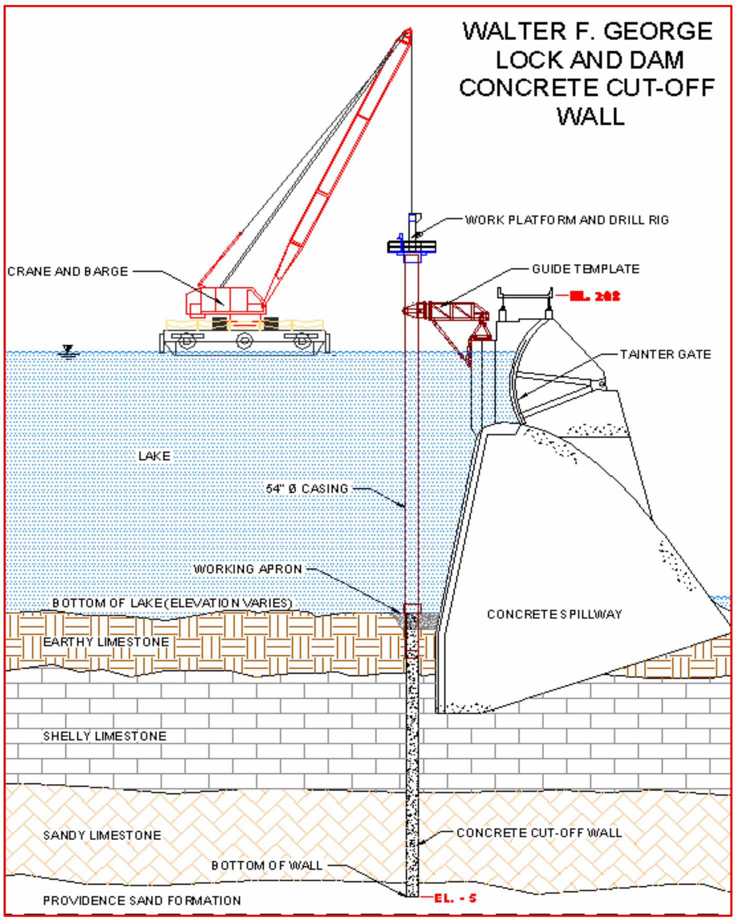

Figure 8. Section of the Secant Pile Wall, W.F. George, AL (Ressi, 2005).

21. MISSISSINEWA, IN (2002-2005)

- Immediate, massive slurry loss occurred in embankment and in bedrock during excavation of first two test panels. This led to intensive pregrouting of alignment to a maximum residual permeability of 10 Lugeons. This exploration, plus subsequent hydromill excavation led to discovery, and cut-off, of 230-foot-deep "feature," using 10-foot-long panels as well as responsive modifications to wall toe elevation elsewhere. Other sections had 25-26-foot Primaries and 10.5-foot closure panels.

22. TAYLORSVILLE, OH (2004)

- Good illustration of the use of granulated blast furnace slag as a construction material, due to its ability to provide low permeability and high strength relative to conventional cement-bentonite wall.

- Design required 28-day UCS over 100 psi and $K < 1 \times 10^{-6}$ cm/s . Typical CB mixes typically provide UCS of 15-30 psi, and $K \sim 1 \times 10^{-6}$ cm/s. Slag cement bentonite mixes typically provide 100 psi and 5×10^{-7} cm/s, respectively.
- Field results gave 108-200 psi (av. 155) and 3.1×10^{-8} cm/s – 5.9×10^{-7} cm/s (av. 2.5×10^{-7} cm/s).

4. CONCLUSIONS AND OBSERVATIONS

4.1 Concrete and Plastic Concrete Walls: Panel Method

(i) Walls have been installed with verifiable verticality and continuity to depths of at least 223 feet (clamshell) and 402 feet (hydromill).

(ii) Such walls can be built with a wide and engineered variety of backfill materials varying from low strength, high deformability plastic concrete, to conventional concrete of high strength.

(iii) Obstructions (natural and artificial) can be accommodated by judicious use of several techniques including pre-excavation (and backfilling), chiseling or the use of the hydromill itself. Lateral tie-in situ into sloping concrete structures and steep valley sides can be accomplished with special care. Rock masses with unconfined compressive strengths of up to, say 10,000 psi (massive), or 20,000 psi (fissile) can be accommodated by the hydromill, although the cost of the penetration rapidly escalates as the higher limits are approached (Stroble and Kleist, 1999).

(iv) These walls can be constructed without having to drawdown the reservoir for that particular purpose provided that slurry can be maintained at least 2 feet above the reservoir elevation at all times.

(v) Related to this observation is the fact that sudden, massive slurry losses have been encountered on several projects and have, on occasions, created fracturing of the embankment. Defenses against this are numerous, ranging from a variety of “in trench” actions, to limiting trench length, to suspension of operations and intensive pregrouting of the embankment and/or bedrock to an acceptable, verifiable residual permeability.

(vi) Such projects typically attract the highest contemporary standards of real time QA/QC and intense dam instrumentation, and require outstanding levels of construction skill and expertise. All these factors are typically inconsistent with the traditional “Low Bid” method of contractor procurement.

(vii) Panel walls can also be “backed up” by very plastic, low permeability panels, to protect particularly sensitive joints or structural connections.

(viii) Technological advances continue especially with hydromill and hydraulic clamshell equipment to improve productivity, reliability and deviation measurement/control.

(ix) Major temporary modifications to the dam crest can normally be anticipated in order to provide a safe, stable and adequate working platform, and/or to reduce the elevation of the top of the wall.

4.2 Concrete Walls: Secant Pile Method

(i) This is intrinsically a more complex and intricate methodology used only where the geological conditions (e.g., particularly hard rock) or the site logistics (e.g., installation of the cut-off through water) eliminate other alternatives. It is rare and relatively expensive.

(ii) With appropriate equipment and procedures, walls of acceptable and verifiable continuity have been constructed to over 280 feet.

(iii) In the event of encountering particularly difficult rock mass conditions, various defenses can be deployed ranging from modified “small hole” techniques (e.g., downstaging) to complete pregrouting of the alignment.

(iv) Technological advances continue, the goals being to improve reliability and deviation/measurement control.

In addition, comments (iv), (vi) and (ix) from Section 4.1 (above) apply.

4.3 Soilcrete Walls: Deep Mixing Method

(i) Applications to date have been relatively few, and have been triggered by mainly logistical and dam safety considerations.

(ii) Depth capability is practically limited to not more than 100 feet, and particularly dense/stiff layers and boulder/cobble "nests" constitute major production challenges. The actual properties of the soilcrete materials may vary widely, and are less precisely controllable, as a cut-off product, than the total replacement materials used in panel or secant walls.

(iii) In appropriate ground conditions, however, the method can provide a very quick and relatively economical alternative, and is particularly well-suited to low embankments, and levee remediation.

(iv) Major developments to the technology, e.g., the TRD Method (Aoi, 2003) Cutter Soil Mix Method (Brunner, 2005) are becoming available which will greatly widen the applicability of the Deep Mixing Method.

In addition, comments (iv), (vi), and (ix) of Section 4.1 above apply.

4.4 Cement-Bentonite and Soil-Cement Bentonite Walls

(i) Such walls have traditionally been employed on relatively small remediations to moderate depths. They employ simple and well-established technology (backhoe) and can give a very reliable, consistent, quick and economical solution.

(ii) However, the work conducted at Twin Buttes Dam has highlighted the technical and economic advantages of using soil-cement-bentonite walls in certain conditions, over huge areas, and employing panel-type installation methodologies (as opposed to backhoe).

(iii) Their constructability is challenged by dense/stiff and bouldery conditions, or where the stability of the trench proves difficult to maintain.

(iv) The recent use of granulated blast furnace slag has been found very beneficial for strength and permeability development.

(v) Excellent laboratory and field data can be cited to support the development of such mixes.

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