Remedial Cutoff Walls for Dams in the U.S.: 40 Years of Case Histories

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ABSTRACT

Since 1975, there has been a rich history of embankment dam remediation in the U.S., mostly to prevent seepage and erosion through and under these structures. The history of these works has been described by many authors, the compendium of Bruce (2012) being the most recent, addressing projects completed up to 2010. Since then, a number of extremely large remediations have been completed, including cutoffs at Clearwater, Wolf Creek, Center Hill, Pine Creek, Bolivar Dams, and Herbert Hoover Dike. Together these more recent projects greatly exceed the combined cost of similar works conducted in the prior 35 years. This paper provides an updated compendium of these projects, and provides detailed references for future researchers to develop.

1. INTRODUCTION

The National Inventory of Dams (NID) has listed over 84,000 dams in the United States which meet its criteria for inclusion (Ragon, 2011), namely:

1. High hazard classification — loss of one human life is likely if the dam fails.
2. Significant hazard classification — possible loss of human life and likely significant property or environmental destruction.
3. Low hazard classification — no probable loss of human life and low economic and/or environmental losses, but the dam:
   - equals or exceeds 25 feet in height and exceeds 15 acre-feet in storage;
   - equals or exceeds 50 acre-feet storage and exceeds 5 feet in height.

Almost 14,000 dams meet Criterion 1. Only 4% (3,075) are federally owned, and these mainly date from the earlier third of the Twentieth Century. Over 87% of the total are primarily classified as earth embankments, while no other category exceeds 3% of the total. The main primary purposes are recreation (35%), flood control (17%), fire protection in stock/small fish ponds (15%) and irrigation (10%), while less than 3% generate power. Many structures are multipurpose. Figure 1 summarizes their completion dates: about 50% were completed between 1950 and 1979, while the median age in the year 2016 is about 65 years.

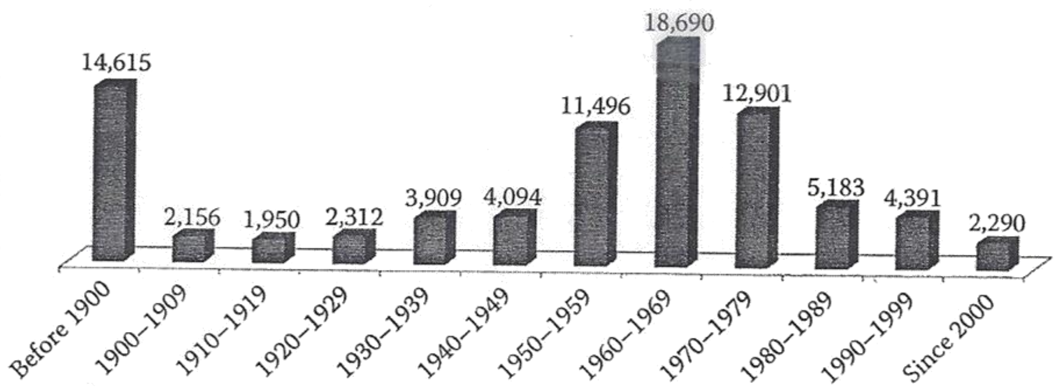

Figure 1. U.S. dams by completion date.
(From National Inventory of Dams, CorpsMAP, http://nid.usace.army.mil, 2010.)

Whereas it may be calculated from the National Inventory of Dams (2010) that the cumulative "end-to-end" length of all the U.S. dams is around 18,000 miles, preliminary estimates put the cumulative length of levees in the U.S. at over 120,000 miles. Only about 14% of this total may be regarded as federal, and referred to by Halpin (2010) as "robust." The balance includes municipal, local and agricultural structures often featuring little engineering design, patchwork construction and minimal periodic maintenance, since they were traditionally regarded as "simple" structures.

Certain design assumptions and construction techniques used in the dams and levees built prior to, say, 1960, would not be acceptable today, and have left behind fundamental flaws in some structures. Appropriate filter criteria for embankments and uplift/sliding issues in concrete dams are two obvious design related examples, while old approaches to rock surface preparation and foundation treatment would also fall into the unacceptable category. In addition, there are two overriding geological considerations which directly influence the serviceability, reliability, and performance of the dam and levee system. These considerations are (i) the presence of solution susceptible carbonate and evaporite formations, and (ii) the potential for seismic activity.

Regarding point (i), there is a huge swath of karstic limestones and dolomites which outcrops from Pennsylvania to Alabama, while Martinez et al. (1998) have estimated that evaporites underly about 40% of the contiguous 48 states. Regarding point (ii), there are highly seismic active zones centered on New Madrid, MO, and Charleston, SC, as well as the more famous organic belts of the Western U.S.

Very simplistically, therefore, geology and seismicity — either alone or together — pose a clear and present threat to tens of thousands of water-retention structures nationwide, but especially to those in the basins of the central Mississippi-Missouri river system and its major tributaries such as the Tennessee and Ohio rivers, and to those in the environs of the greater Rocky Mountain chain. To these concerns must be added the more transient, but equally destructive, threat posed by extreme weather events to levees all across the country, but especially in the upper Midwest, the lower Mississippi, and central California. The problem in the New Orleans area is exacerbated by the continual regional settlement of the entire delta area, estimated at up to ½ inch per year.

Galvanized by the Gulf Coast tragedy of August, 2005, the federal government, in the form of the USACE (U.S. Army Corps of Engineers), developed and implemented a radically different approach to dam-remediation prioritization, building on the pioneering expertise and experience from the Bureau of Reclamation. This "risk-based" or "risk-informed" approach has since become a model for other bodies with large portfolios of dams, including the Tennessee Valley Authority and the larger utilities. This new approach has been the catalyst for the prioritized and expedited repair of many major structures in recent years.

2. BASIC CLASSIFICATION OF CUTOFF WALL TECHNOLOGIES

Cutoff walls for existing structures can be divided fundamentally into two categories (Bruce, 2012):

- <u>Category 1</u> cut-offs involve backfilling of a trench or shaft previously excavated under bentonite slurry or similar supporting medium. Construction involves the use of backhoes, grabs, hydromills and/or secant pile rigs.
- <u>Category 2</u> cut-offs involve the mixing of the fill and/or foundation soils in situ. Examples include conventional (i.e., vertical axis) Deep Mixing Methods (DMM), the TRD Method and the CSM Method.

The prime subject of this paper is the Category 1 cutoffs, because they have been employed most frequently in dams, given their undisputable advantages in terms of depth and geological application. However, it would be remiss not to first acknowledge the rich history of Category 2 structures in dam and levee remediation.

Traditional, vertical axis Deep Mixing Methods (DMM) have been used since 1987 on many dam and levee remediation projects throughout the U.S. Most notable have been seepage cutoffs at Cushman Dam, WA (1992), Sacramento Levees, CA (1990 and 2003), Lewiston Dam, ID (2001), and seismic remediations at Jackson Lake Dam, WY (1988), Sunset North Basin Dam, CA (2006), Clemson Diversion Dams, SC (2005), and San Peblo Dam, CA (2009). In addition, the massive seismic retrofits at Wickiup Dam, OR (2002) and Tuttle Creek Dam, KS (2007) were undertaken with jet grouting and cement-bentonite walls, respectively, although both were initially candidates for some type of DMM treatment (Stare, et al., in Bruce, 2012). A prime area for the use of conventional DMM has been in the New Orleans area, for the strengthening of very soft foundations prior to rebuilding levees higher than previously existing. A detailed history of this work is provided by Bruce, et al., 2012, while by far the biggest project (LPV 111) was completed in 2011 and is described by several authors in the New Orleans Conference (2012) and in other sources (Schmutzler and Pagliacci, 2012; and Schmutzler and Leoni, 2013).

The LPV 111 project is likely the largest DMM application completed outside Japan, and the 5 miles of raised, rebuilt levee are an essential component of the New Orleans Hurricane Protection System. Two different types of DMM, including the jet-assisted "Turbomix" type, were used to create columns 5 feet in diameter, overlapping to create panels of soilcrete orthogonal to the levee axis. These panels were around 70 feet deep, and 60 feet wide, and were spaced at 16- foot centers for the whole alignment. This involved over 30,000 discrete columns to treat over 1.6 million cubic yards of soil. The work was conducted from January 2010 to March 2011, and used 8 DMM rigs and grout plants. Over 460,000 tons of slag-cement binder was placed. Of particular interest is the fact that the USACE employed the Early Contractor Involvement (ECI) process to expedite contractor selection and the project schedule, while at the same time permitting the contractor an intense and meaningful involvement in the design and specification of the project. Further, much of the DMM return material was found suitable for use in building the core of the new levee, in lieu of typical clay backfill — a considerable cost and schedule advantage.

In recent years, considerable use has been made of the two variants of DMM, new to the U.S. One is the TRD Method (trench remixing and cutting, deep) which, in very simple terms, is a large and very powerful chain saw which progresses laterally through the ground, cutting and blending (with grout) to create a continuous soilcrete wall. Developed in Japan in 1993-1994, it is capable of producing a cutoff from 2 to 3 feet thick, to depths approaching 180 feet, even in dense and bouldery soils, provided they are “rippable.” There have been several applications in the U.S. since its introduction in 2006, with the biggest, by far, being at Herbert Hoover Dike, FL, where 5 miles of wall as deep as 80 feet were constructed. The vertical nature of the cutting and blending process provides a high degree of homogeneity in the soilcrete, although care must be taken to compensate for thermally-induced stresses during curing. Production rates have been found to be extremely high in appropriate conditions, and the environmental impacts are minimal (Burke, et al. in Bruce, 2012).

The second, newer DMM variant widely seen in levee remediation is CSM (Cutter Soil Mix). The technique is a joint German-French development, commencing in 2003, and building on experience with hydromill (trench cutter) and conventional DMM techniques. Kelly-mounted CSM can comfortably reach depths of 100 feet, while newer cable-suspended cutters are reportedly capable of over 180 feet depth. Wall thicknesses of 2 to 4.5 feet are feasible and, like TRD, can provide soilcrete of excellent homogeneity, with high degrees of real time QC. Again the largest project yet conducted was at Herbert Hoover Dike, FL, where CSM was used to install about 12 miles of soilcrete cutoff, in several different phases. One of the inherent advantages of the CSM method is that the cutter itself can be mounted on non-specialized carriers. Thus, CSM is found to be competitive on quite small projects also, because the costs of mobilization are moderate (Weidenmann, in Bruce, 2012).

Most recently, and as described in other papers in this Conference, conventional DMM has been used on the massive seismic retrofit of Perris Dam, CA, and for construction of a cutoff at Buckeye Lake Dam, OH. In the latter case, there was a rare opportunity to compare the relative performances of two distinctly different types of Category 2 walls, namely DMM, and the DeWind “One Pass” system, not dissimilar to TRD in basic concept. The DeWind method has now been used on several major cutoffs and is quickly gaining both technical reputation and market share.

Reverting to Category 1 walls for dams, these are built through and under existing structures by first excavating the in-situ materials, and thereafter filling the excavation with an engineered “backfill,” typically cement based. During the excavation phase, the trench or panel must be stabilized against collapse by employing a bentonite or polymer slurry. Only when the cutoff is being built in rock by the secant pile method, is it not necessary to use such slurry, although other methods such as full-length, temporary casing are required in extreme conditions.

An earlier review by Bruce et al. (2006) detailed 20 North American dams (including one in Canada) which had been remediated by such diaphragm walls in the period 1975-2005. These are shown in Figure 2, and represent almost 7,500,000 ft^2 of cutoff wall. These walls in dams were constructed by three methods: clamshell (about 50% total area); hydromill (about 35%); and secant piles (about 15%). The majority of the projects, and all of the later ones, have used concrete (conventional or occasionally “plastic”) as the backfill, although one (Addicks and Barker, TX, 1978-1982) used soil-bentonite, and another (Twin Buttes, TX, 1996-1999) used soil-cement-bentonite. The deepest clamshell wall (Wells Dam, WA) reached 223 feet, and the

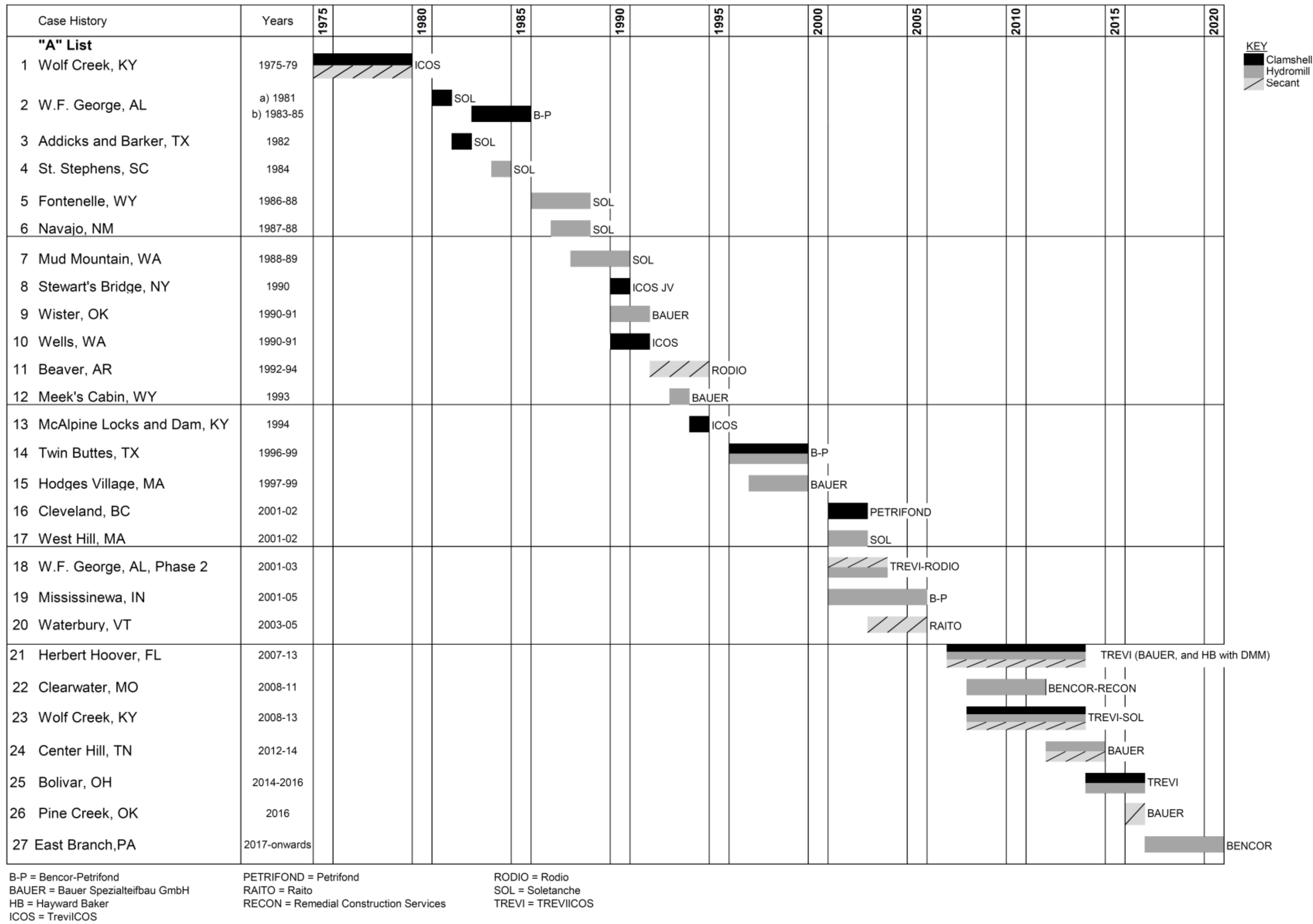

Figure 2. List of remedial cutoffs for dams showing principal construction method and specialty contractor.

deepest hydromill wall (Mud Mountain, WA) reached over 400 feet. The maximum depth reached by secant piles is 280 feet (Wolf Creek, KY). These projects have had minimum wall widths of 1.5 to 3.1 feet, with most being in the range 2 to 3 feet.

Clearly, the intrinsic advantage of Category 1 walls is that the resultant cut-off material (i.e., the “backfill”) can be engineered to provide an extremely wide range of properties, independent of the native material through which the cut-off is to be excavated. This ability is so fundamental that the actual cut-offs are primarily called after the materials themselves, as opposed to the method of excavation:

- conventional concrete walls
- plastic concrete walls
- cement-bentonite walls (CB)
- soil-bentonite walls (SB)
- soil-cement-bentonite walls (SCB)

In all cases except CB walls, excavation is conducted under bentonite (or polymer) slurry which is thereafter displaced out of the trench or panel by the backfill material of choice. It is generally believed that the concept of excavating under a bentonitic supporting slurry was first conceived by Veder, in Austria, in 1938, while the first U.S. application was in 1962 (Xanthakos, 1979). The relationship between backfill material and excavation method is summarized below.

TYPE OF BACKFILL	EXCAVATION METHOD			
	CLAMSHELL	HYDROMILL	BACKHOE	SECANT PILES
Conventional Concrete	Typical	Typical	Not feasible	Typical
Plastic Concrete	Feasible	Feasible	Not conducted	Rare
CB	Feasible	Feasible	Common	Not conducted
SB	Not conducted	Not conducted	Very common	Not conducted
SCB	Very Rare	Very Rare	Common	Not conducted

Details of the various excavation methods are provided in older fundamental texts such as Xanthakos (1979) and ASTM (1992), while Bruce et al. (2008) and Bruce (2012) summarize case histories of more recent vintage. Much valuable information may also be obtained in the websites of the major contractors and equipment manufacturers. The following notes are provided by way of introduction, and perspective.

It is often the case that all three techniques may be used on the same project: the backhoe to excavate a “pre-trench,” say 20-40 feet deep, the clamshell to excavate through unobstructed fill or soil, and the hydromill to cut into the underlying or adjacent rock. Furthermore, the recent cut-off installation at Wolf Creek Dam, KY, features a combination of panel wall (by clamshell and hydromill) and secant pile technologies, such are the challenges posed by the geological conditions and dam safety concerns during construction.

Each of the different methods has been used successfully and safely on existing dams and levees. The choice of method is primarily dictated by the geotechnical conditions, the depth of the cutoff, dam safety considerations, and the traditional preferences of the respective specialty contractors.

3. UPDATED LIST OF CASE HISTORIES

Appendix 1 to this paper provides an updated list of Category 1 cutoffs, referred to above in Figure 2. An enormous amount of work has been conducted for the USACE in the last ten years or so, to remediate firstly four major DSAC-1 Category Dams (highest risk) and more recently the most needy of the DSAC-2 Category Dams (slightly lower risk). It may be estimated that the dollar value of the "new" remediations (i.e., Clearwater, MO, Herbert Hoover, FL, Wolf Creek, KY, Center Hill, TN, Bolivar, OH, Pine Creek, OK, and East Branch, PA) conducted in the last ten years is several times that of the combined expenditure (in current dollars) of the preceding 30 years.

4. FINAL REMARKS

It is clear when studying the numerous technical papers on these projects – and having been involved in one way or another with all of them – that the major technological breakthrough in recent years was the work conducted at Wolf Creek Dam, KY. This is not to short sell the innovative construction methods adopted by three different contractors at Herbert Hoover Dike, FL. However, the standards set in quality control and assurance, in Data Management Systems, in construction methodologies, and in Dam Safety Management at Wolf Creek truly represented a "great leap" forward. As one direct consequence, Owners are now being more prescriptive in their specifications, such is their confidence in the wonderful database of knowledge that has been forthcoming.

It is highly unlikely that the dam remediation market in the U.S. will ever again see the sustained levels of activity which characterized the decade from 2007. However, there is absolutely no doubt that *some* level of activity will endure, and that, in all likelihood, it will be characterized by safe and effective solutions in an increasingly competitive commercial atmosphere.

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APPENDIX 1

Details of Remedial Dam Cutoff Projects using Category 1 Panel or Secant Concrete Cutoffs
1975-2016

Dam Name and Year of Remediation	Contractor	Type of Wall	Composition of Wall	Ground Conditions	Purpose of Wall	Scope of Project				References
						Area	Min. Width	Depth	Length	
1. WOLF CREEK, KY. 1975-1979	ICOS	24-inch diameter Primary Piles, joined by 24-inch wide clamshell panels. Two phases of work.	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. W.F. GEORGE, AL. 1981	Soletanche (Phase 1)	26-inch thick panels using cable and kelly-mounted clamshell	Plastic Concrete.	Random, impervious FILL with silty core over 25-30 ft ALLUVIUM over chalky LIMESTONE	To provide a "positive concrete cut-off" through the dam and alluvials.	130,000 sf (Phase 1) plus	26 in	Max 138 ft	Approx. 1,000 ft	• Soletanche Brochure (undated)
1983-1985	Bencor-Petrifond (Phase 2)	24-inch panels 15-27 ft long	3,000 psi Concrete			951,000 sf (Phase 2)	24 in	110-190 ft	8,000 ft	• Bencor Brochure (undated)
3. 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.
4. 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)

* 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 Remediation	Contractor	Type of Wall	Composition of Wall	Ground Conditions	Purpose of Wall	Scope of Project				References
						Area	Min. Width	Depth	Length	
5. 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)
6. 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)
7. MUD MOUNTAIN, WA. 1988-1990, (Mainly over period December 1989 to April 1990)	Soletanche	33- and 39-inch-thick panel 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 abut-ments, 39 in in center	Max 402 ft	700 ft	• Soletanche brochures • Eckerlin (1993) • ENR (1990) • Davidson et al. (1991) • Graybeal and Levallois (1991)
8. STEWART'S BRIDGE HYDRO, NY 1990	ICANDA-ICOS	30-inch panel walls installed by clamshell	Plastic Concrete.	FILL over stratified SAND	To prevent seepage through and under the dam.	95,000 sf	30 in	Max 110 ft	About 1,000 ft	• DiCicco (2007) Personal Communication
9. WISTER, OK. 1990-1991 (6 months)	Bauer	24-inch-thick panel wall installed by Hydromill.	Plastic concrete.	Dam FILL, over 30 ft 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)
10. 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 cut-off 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 Remediation	Contractor	Type of Wall	Composition of Wall	Ground Conditions	Purpose of Wall	Scope of Project				References
						Area	Min. Width	Depth	Length	
11. 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)
12. 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)
13. 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)
14. 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)

Dam Name and Year of Remediation	Contractor	Type of Wall	Composition of Wall	Ground Conditions	Purpose of Wall	Scope of Project				References
						Area	Min. Width	Depth	Length	
15. HODGES VILLAGE, MA. 1997-1999	Bauer of America	31.5-inch-wide panel wall formed by hydromill plus use of grab for initial excavation and boulder removal.	Concrete.	Homogeneous permeable sand and gravel FILL over stratified glacial OUTWASH sands, gravels and cobbles over MICA SCHIST.	To prevent seepage through the dam and foundation.	185,021 sf (dam) plus 75,486 sf (dike)	31.5 in	Max 143 ft (avg. 89 ft) including 5 ft into rock (dam) plus Max 77' (avg. 57') including 5 ft into rock (dike)	2,078 ft (dam) plus 1,315 ft (dike)	• Dunbar and Sheahan (1999) • USACE (2005)
16. CLEVELAND, BC. 2001-2002 (4 months)	Petrifond and Vancouver Pile Driving	32-inch panel wall constructed by cable suspended clamshell.	Plastic Concrete.	Heterogeneous glacial sediments including SILT, SAND, GRAVEL and TILL with hard igneous boulders.	To prevent seepage through glacial and interglacial foundation sediments, especially 20-ft sand layer.	55,000 sf (est)	32 in	20 to 75 ft	1,004 ft	• Singh et al. (2005)
17. WEST HILL, MA. 2002-2002	Soletanche-McManus JV	31.5-inch panel wall constructed by hydromill plus clamshell for pre-excavation.	Concrete.	Zoned random and impermeable FILL over permeable stratified sand and gravel. Glacial OUTWASH over GRANTITE GNEISS.	To prevent seepage through the foundation.	143,000 sf	31.5 in	Max 120 ft including 2 ft into rock (avg. 69 ft)	2,083 ft	• USACE (2004)
18. 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 ft of water over LIMESTONE with light karst, and very soft horizons (rock strength over 14,000 psi in places).	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)

Dam Name and Year of Remediation	Contractor	Type of Wall	Composition of Wall	Ground Conditions	Purpose of Wall	Scope of Project				References
						Area	Min. Width	Depth	Length	
19. MISSISSINEWA, IN. 2001-2005 (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.	427,308 sf (330,127 embank-ment plus 97,181 in rock)	30 in	123 to 230 ft (including max 148 ft into limestone) av. 180 ft	2,600 ft	• Hornbeck and Henn (2001) • Henn and Brosi (2005)
20. WATERBURY, VT. 2003-2005	Raito	18-inch-thick secant wall using 79-inch piles at about 66-inch centers.	Concrete in lower 100 ft, permeable backfill above.	Zoned EARTHFILL dam over permeable GLACIAL DEPOSITS with detached rock slabs and MICA SCHIST.	To prevent seepage and piping in the glacial gorge.	20,000 sf designed but only 13 of 22 piles completed	18 in	125-180 ft (avg. 163 ft) with “anomaly” to 222 ft, including 10 ft into rock	124 ft designed	• USACE (2006) • Washington (2005)
21. HERBERT HOOVER, FL. 2007-2013	TREVIICOS (Hydromill) / Hayward Baker (TRD) / Bauer Foundations (CSM)	24 to 36-inch-thick wall: performance specification with different methods.	Soil-cement-bentonite (TRD,CSM) and CB (TREVIICOS)	Heterogeneous FILLS and peat over SANDS, SILTS and LIMESTONE.	To prevent seepage and internal erosion (partial penetration)	About 7 million sf	24 in	60-80 ft	22 miles	• Mauro et al. (2012) • Bruce (2012) • New Orleans (2012)
22. CLEARWATER, MO. 2008-2011	Bencor-Recon JV	Min. 24-inch-thick wall with clamshell and hydromills.	Concrete.	Dam FILL over karstic LIMESTONE.	Cutoff through epikarst and into limestone as part of Composite Cutoff Wall.	772,000	32 in	120-200 ft Including 40 ft into rock	4,080 ft	• Harris (Personal Communication 2016)
23. WOLF CREEK, KY. 2008-2013	TREVIICOS - Soletanche JV	6-foot-thick PCEW in embankment, 50-inch diameter secant piles below at 31-inch centers.	Concrete.	Dam FILL over karstic LIMETSTONE.	Cutoff through epikarst and into limestone as part of Composite Cutoff Wall.	980,000 sf including about 650,000 sf PCEW	24 in	Max 277 ft	3,800 ft	• Bassola et al. (2013) • Bedford et al. (2013) • Vannoy and Morales (2013)
24. CENTER HILL, TN. 2012-2014	Bauer Foundations	7.4-foot-thick PCEW in embankment and 30-inch hydromill below Some secant sections to 186 feet.	Concrete	Dam FILL over karstic LIMETSTONE.	Cutoff through epikarst and into limestone as part of Composite Cutoff Wall.	200,000 sf of cutoff including 100,000 sf PCEW	Min. 30 in	Max 300 ft	900 ft	–

Dam Name and Year of Remediation	Contractor	Type of Wall	Composition of Wall	Ground Conditions	Purpose of Wall	Scope of Project				References
						Area	Min. Width	Depth	Length	
25. BOLIVAR, OH. 2014-2016	TREVIICOS	Min. 24-inch-thick wall with clamshell and hydromill.	Plastic Concrete	Dam FILL over GLACIAL OUTWASH over various SEDIMENTS.	Positive cutoff for flood control dam.	600,000 sf	36 in	30-144 ft	4,500 ft	• Taylor et al. (2016) • Santillan and Hleplas (2015)
26. PINE CREEK, OK. 2016	Bauer Foundations	Drilled and cased secant piles. Minimum 36-width.	Concrete	Random embankment, FILL over SANDSTONE.	Positive cutoff to intercept a fracture above a culvert.	14,000 sf approx.	60 in	88 to 117 ft Incl. 2 ft into rock	133 ft	• White (Personal Communication 2017)
27. EAST BRANCH, PA. 2017 onwards	Bencor	Clamshell, hydromill and secant 18-inch min.	Concrete	Dam FILL over COLLUVIUM and ALLUVIUM over SANDSTONE.	Full length, full depth seepage cutoff	404,232 sf	32-42 in	Max 260 ft and up to 170 ft in bedrock	2,350 ft	• Greene and Sekela (2007) • Greene and Sekela (2008) • Greene et al. (2010)