# Cutoff Walls for Dams and Levees

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*During the last 10 years, there have been unprecedented levels of activity in the field of dam and levee remediation in the United States. This is reflective of the deterioration of the nation's infrastructure, and also the widespread application of Risk Based Analyses to efficiently identify and prioritize high risk structures and the need to remediate them with urgency. This process has been especially prevalent since the aftermath of Hurricanes Katrina and Rita in the Fall of 2005. The paper describes the current state of practice in the use of the following specialty construction techniques: drilling and grouting; Category 1 Cutoff Walls (excavate and replace); Category 2 Structures (mix in-situ); and rock anchors.*

***Keywords*: cutoffs, dams and levees, deep mixing, diaphragm walls, materials, secant piles**.

## 1. Introduction

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

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 8 m in height and exceed 15 acre-feet in storage;
   Equals or exceeds 50 acre-feet storage and exceeds 1.8 m 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 pond (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 2013 is about 62 years.

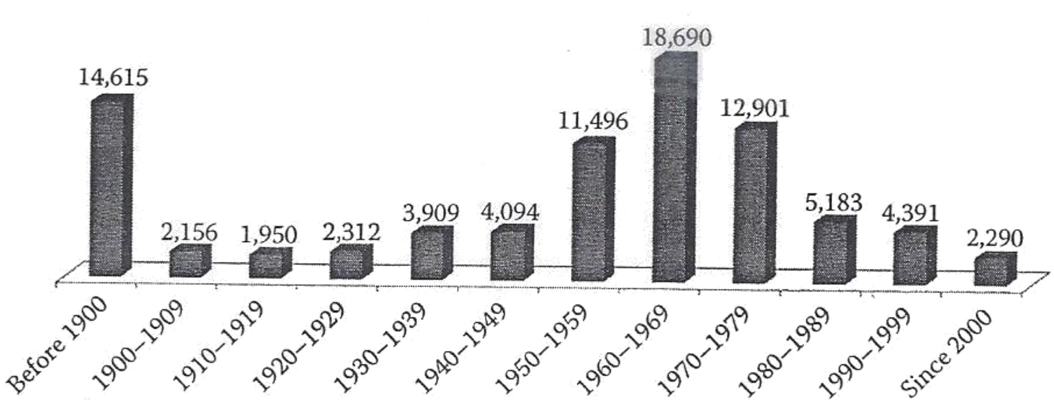


***Figure 1: U.S. dams by completion date. (From National Inventory of Dams, CorpsMAP, http://nid.usace.army.mil, 2010.)***

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 26,000 km, *preliminary* estimates put the cumulative length of levees in the U.S. at over 180,000 km. 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 having had little formal 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 limestone and dolomite 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 2 to 12 mm 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 expedited repair of many major structures in recent years, the subject of this paper, although, of course, dam remediation in some form has been around since dam construction.

## 2. Drilling and grouting

Until the mid-1990's, rock grouting in the U.S. was technologically far behind practices employed in many other parts of the world, and especially in France, Germany, Italy and Switzerland. There were many reasons for this, arguably the strongest being (i) the widespread application of very prescriptive specifications (often first developed in the 1930's) and the associated "low bid" environment, and (ii) the option, in such a large country, to "walk away" from a proposed site rather than deal with particularly difficult geological challenges.

Recent triggers for innovation include (i) a strong influence from foreign consultants and contractors, (ii) the challenge to remediate projects in-situ (i.e., no "walk away" option), and (iii) rapid developments in grouting materials and automated monitoring and control. Full documentation of recent advances may be found in the Proceedings of the New Orleans Conferences of 2003 and 2012, and in the textbooks by Weaver and Bruce (2007) and Bruce (2012). These sources also identify the huge scale of many of the recent projects — especially those conducted for the USACE in karstic limestone conditions — and the very low, verified residual permeability of the treatment.

The major elements of this technological revolution may be summarized as follows:

- The use of rotary sonic and dry, double-head duplex drilling techniques for safely penetrating existing embankments.
- The use of Multiple Packer Sleeved Pipe (MPSP) techniques for effectively sealing the plastic standpipes into the embankment and — crucially — for thoroughly treating the embankment/rock interface, and the uppermost grout stage.
- The use of water-powered, down-the-hole hammers (Wassara) for rock drilling is now proving to be the state of practice.
- The routine use of multipressure Lugeon testing in Exploratory and Verification holes, and single pressure tests in all other stages.
- The development of suites of stable multicomponent, balanced, cementitious grouts with excellent bleed, pressure filtration and rheological properties.
- The routine use of computer systems to record, control, illustrate and analyze all water testing and grouting activities, in real time. This has also permitted higher effective pressures to be safely used.
- Grouting of every stage to a prescribed grout refusal criterion, currently between 1 and 3 l/min. depending on project conditions.
- The concept of "Quantitatively Engineered Grout Curtains" (Wilson and Dreese, 2003) wherein the target residual permeability of the curtain is logically designed, and verified in the field.
- The growing use of Optical and Acoustic Televiewers, which provide "virtual" core even in non-cored holes.
- The growing use of "best value" as opposed to "low bid" contracting. This has stimulated a remarkable increase in the quality of the capabilities and performance of the specialty contractors.

## 3. Category 1 cutoff walls: excavated and backfilled

Such walls 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 750,000 $m^2$ of cutoff wall.

These walls in dams have been 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 74 m, and the deepest hydromill wall (Mud Mountain, WA) reached 120 m. The maximum depth reached by secant piles is 85 m (Wolf Creek, KY). These projects have had minimum wall widths of 0.5 to 1 m, with most being in the range 0.7 - 0.9 m.

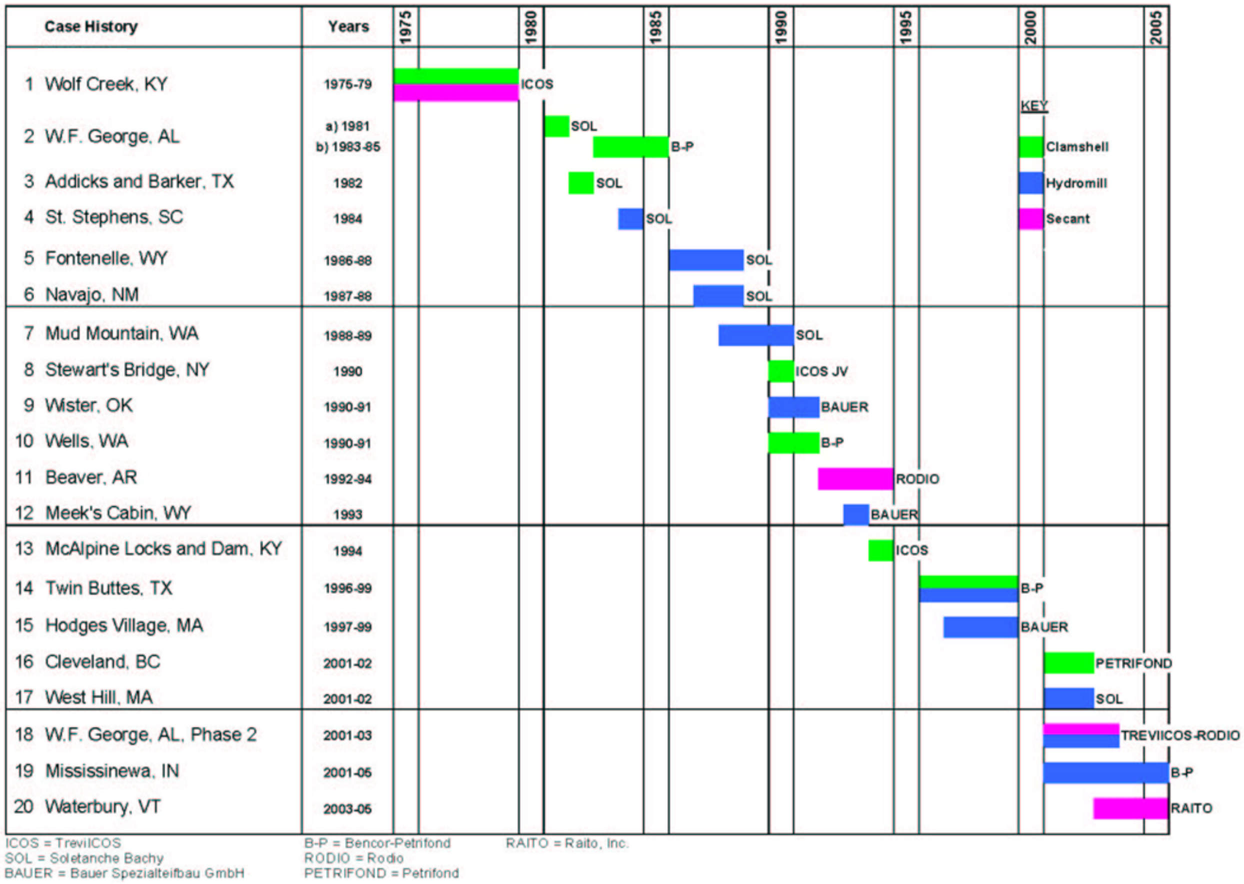


***Figure 2: Progression of construction since the first remedial cutoff at Wolf Creek Dam, KY, in 1975.***

Since the initial study, several other major structures have been remediated with deep Category 1 cutoffs, including A.V. Watkins, UT (featuring a cement-bentonite backfill), Clearwater, MO, Wolf Creek, KY and Center Hill, TN, while several more are in the final stages of detailed design and preparation of bid documents. Regarding these newer projects, details from two, namely Clearwater Dam and Wolf Creek, follow. At the former site, the discovery of a major sinkhole in the embankment in 2002 led to firstly an emergency grouting project, followed by a more intensive karstic feature treatment using High Mobility Grout (HMG) and Low Mobility Grout (LMG) (to 120 m total depth) and an extensive deep grout curtain. The latter curtain was completed in 2009, and included more than 31,000 lm of embankment drilling, and 36,000 lm of rock drilling. This curtain was part of the "Composite Wall" concept (Bruce et al., 2012) wherein the entire alignment of the subsequent concrete cutoff wall is pregrouted in advance, partly to guard against sudden and potentially catastrophic loss of slurry during the excavation of the wall. This had happened at Mississenewa Dam, IN, in 2002 in similar geological conditions. The subsequent concrete cutoff wall, constructed through the dam and the epikarst and a fixed distance into sounder limestone, was 1,400 m long, 0.8 m wide, and a maximum of 65 m deep. It comprised over 39,000 m$^2$ of excavation in embankment and pretreated epikarst, plus over 25,000 m$^2$ in the less karstified limestone at greater depths.

Wolf Creek Dam features the most extensive seepage remediation yet conducted on a U.S. dam, and has been the subject of several successive phases of remediation including the massive grouting effort of the late 1960's, and the pioneering cutoff wall — a combination of piling and clamshell technology — of the 1975-1979 era. However, a deteriorating situation had been recognized by 2006, and, as a prelude to the construction of a placement cutoff wall — larger and deeper than the original — a two-line grout curtain, 1,300 m long, was installed in the most critical area. This featured over

57,000 lm of overburden drilling, over 75,000 lm of rock drilling, and almost 3,000,000 liters of stable grout. This curtain was then further lengthened under the subsequent contract for the cutoff wall, which is 1,250 m long and a maximum of 82 m deep. A hydromill wall, 1.8 m thick, was then built through the embankment (Protective Concrete Embankment Wall – PCEW), and 0.6 m into the underlying rock. The interface had also been treated with Low Mobility Grout (LMG). Thereafter, the 1,197 secant piles, each 1.26 m in diameter, were drilled through the PCEW and into rock, to form the secant pile wall with a minimum, verifiable overlap of over 0.73 m. Extreme measures were taken to limit deviation off vertical to a maximum of 0.25% depth. The total area is over 93,000 $m^3$, and the average measured in-situ permeability $1x10^{-7}$ cm/s. The wall was completed in March, 2013. The overall cost of the most recent phase of remediation of this 1951 dam was 594 million dollars, according to ENR (2012). A similar methodology is anticipated for use at the USACE's Center Hill Dam, where similar geological challenges exist. An intensive deep grout curtain has already been installed under this dam as a prelude to the cutoff wall construction.

In contrast, Category 1 walls for levees have typically featured the use of a long-reach backhoe for excavation under slurry. The first such wall was built in the U.S. in 1948, and thousands of projects using this technique, typically with soil-bentonite or soil-cement-bentonite backfill, have been built. Several examples of backhoe walls are provided by Jasperse (in Bruce, 2012), while the same technique was also used for the 8 km long cement-bentonite cutoff at A.V. Watkins Dam, UT. (One of the largest such walls yet constructed in the U.S.) Another exception to the "backhoe paradigm" for repairing levee-type structures is the recently completed cutoff walls for the Herbert Hoover Dike in Florida. There, the very heterogeneous embankment and foundation conditions proved unsuitable for the use of a backhoe, even though the depth of the wall was well under 33 m. Of the total of 33 km of cutoff completed between 2008 and 2012, 12 km were installed with a clamshell-hydromill combination, and a cement-bentonite backfill. The remaining 21 km were installed as Category 2 walls, further described below.

## 4. Category 2 cutoff walls: mixed in place

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 1.5 m in diameter, overlapping to create panels of soilcrete orthogonal to the levee axis. These panels were around 21 m deep, and 18 m wide, and were spaced at 5 m centers for the whole alignment. This involved over 30,000 discrete columns to treat over 1.4 million cubic meters 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 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 0.7 - 0.9 m thick, to depths approaching 55 m, 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 7 km of wall as deep as 24 m were constructed. The vertical nature of the cutting and blending process assures an exemplary 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 33 m, while newer cable-suspended cutters are reportedly capable of over 55 m depth. Wall thicknesses of 0.6 - 1.4 m are feasible and, like TRD, can provide soilcrete of excellent homogeneity, with high degrees of QA/QC. Again the largest project yet conducted was at Herbert Hoover Dike, FL, where CSM was used to install about 17 km 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).

## 5. Conclusion

A wide range of specialty construction techniques has been developed for use in remediating dams and levees throughout the United States, and the intensity of the work has been unsurpassed. The variety and complexity of these techniques reflect the particular challenges of the dam and levee environment, and the efforts of a relatively small band of highly competitive, skilled and experienced specialty contractors. The projects are being designed and monitored by the owners and/or their consultants, using state-of-the-art methods of investigation, analyses and quality assurance.

While it would appear that the most vulnerable projects have now been addressed, the sheer size of the dam and levee inventory, aging and deteriorating, ensures that the market will remain active for grouting, cutoff walls, and deep mixing for decades to come.

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