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**SEEPAGE CUTOFFS FOR DAMS AND LEVEES: LESSONS LEARNED
FROM 40 YEARS OF REMEDIAL CONSTRUCTION IN NORTH AMERICA ***

Donald A. Bruce

President, GEOSYSTEMS, L.P.

U.S.A.

1. INTRODUCTION

The National Inventory of Dams (NID) has listed over 84,000 dams in the United States which meet its criteria for inclusion [1], 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

* MURS PARAFOUILLES POUR DES BARRAGES ET DES LEVÉES : LES LEÇONS ONT APPRIS DE 40 ANS DE CONSTRUCTION RÉPARATRICE EN AMÉRIQUE DU NORD

completed between 1950 and 1979, while the median age in the year 2018 is about 67 years.

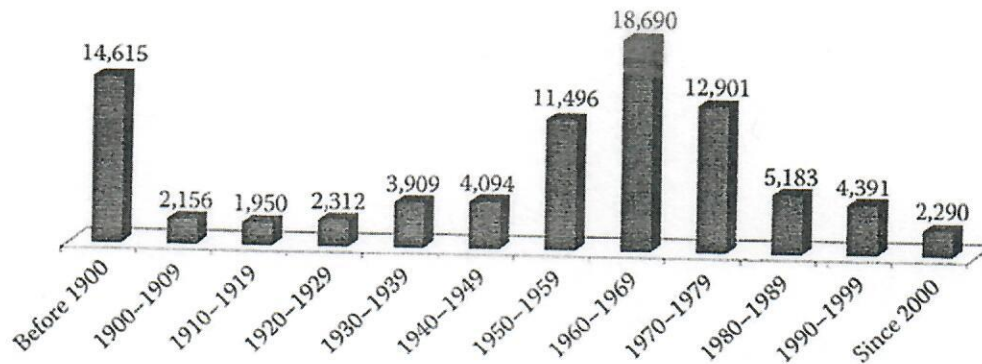


Fig 1

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 [2] 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 considered by Halpin [3] 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 carbonate and evaporite formations, and (ii) the potential for seismic activity.

Focusing on point (i), there is a huge swath of karstic limestones and dolomites which outcrops from Pennsylvania to Alabama, while it is estimated [4] that evaporites underlie about 40% of the contiguous 48 states. These potentially soluble and erodible foundation conditions underlie many of the major river basins, such as the Mississippi-Missouri basin, and the Tennessee and Ohio River Valley systems – and, of course, the aging dams built thereon.

Beginning with the first Wolf Creek Dam KY remediation in 1975, one can tabulate 27 major cutoff walls which have been built through and under the existing embankment dams, to counteract increasing seepage trends, and the erosional dangers these seepages pose to dam and foundation alike. This paper presents the lessons learned from these projects.

2. SUMMARY OF CASE HISTORIES (1975-2017)

A recent review [5] provides details of 27 major remedial cutoffs using “excavate and replace” methods, as opposed to “mix in place” methods [6]. These projects are listed in Figure 2 which also shows the principal construction method and Specialty Contractor. One project remains in progress (East Branch Dam, PA), while three others are foreseen to commence in 2018, including two in Tennessee and the second phase of Herbert Hoover Dike, FL. Details of construction methods and cutoff material design are provided in older texts (such as [7]), while many of the more recent case histories referred to in Figure 2 are summarized more recently in reference [6]). Several different methods of constructing cutoffs have been successfully and safely utilized on these projects, including the use of clamshells, hydromills and large diameter rotary drills. 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. LESSONS LEARNED

3.1. DESIGN CONSIDERATIONS

3.1.1 *Geological and Geotechnical Site Characterization*

The following observations are provided, for brevity and clarity, in bullet form. Some readers may find certain lessons to be self-evident and not worthy of consideration. However, each topic has its roots in situations personally observed by the author and, in his opinion, each merits inclusion.

- Before designing a new program of investigation, very carefully reexamine existing, historical information (e.g., grouting programs, original site investigation data, construction photos, as-built drawings), and dam performance data, especially “signs of distress” (sinkholes, seepages, depressions, erratic piezometer readings, etc.). The work product is a basic but robust hydrogeological model.
- The intensity of the new investigation must reflect the variability of the ground conditions as interpreted from the preexisting hydrogeological model (but will be, practically, governed by budget and access, and the project risks).
- Drill holes must extend over the entire length and depth of a foreseen cutoff. Their location should reflect what is suspected to be the main risk areas identified in the preexisting hydrogeological model.

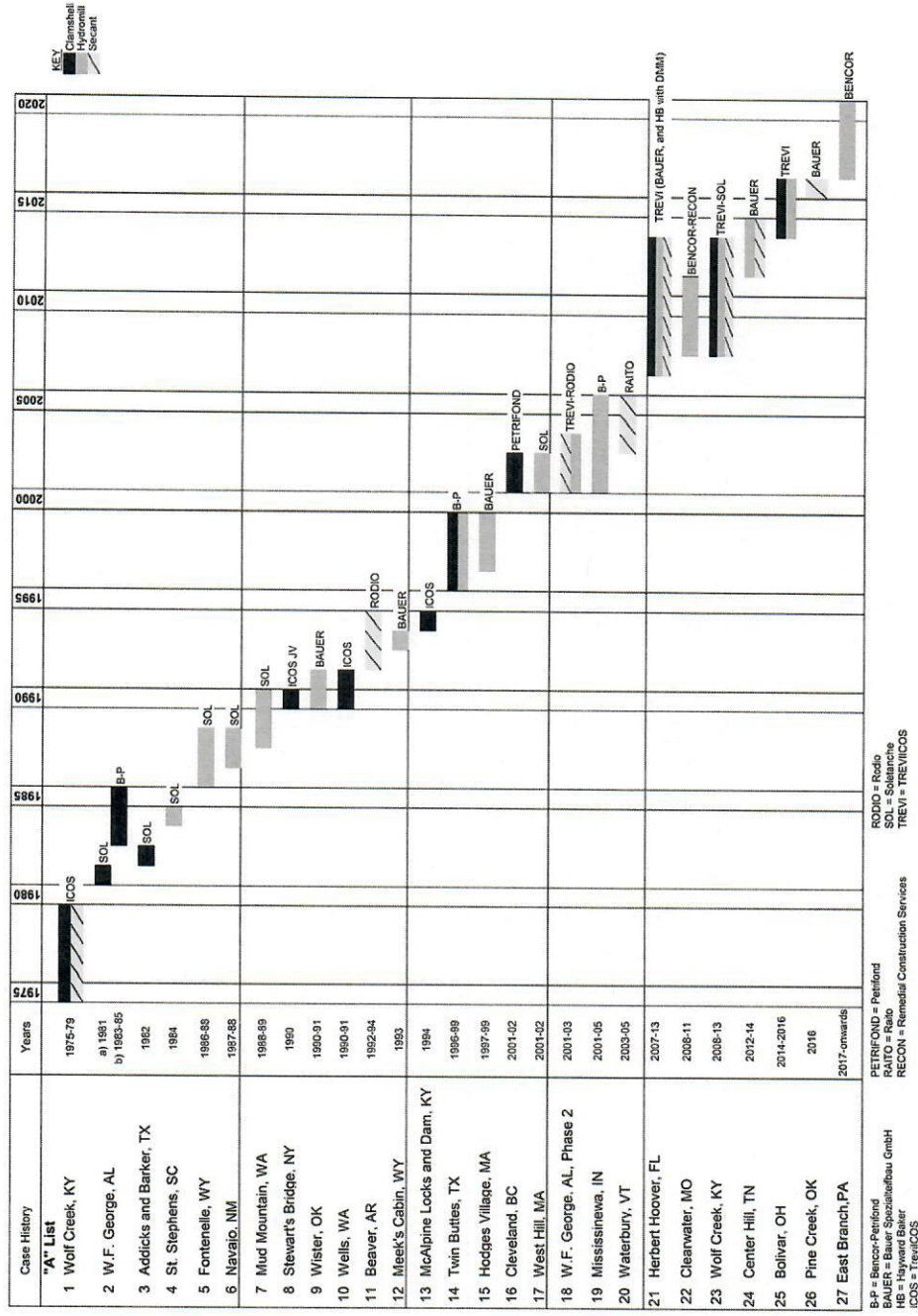


Fig 2

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

- The investigatory program must inform the design of the cutoff, and produce information essential for bidders to select their construction methods, estimate productivities, and evaluate construction risks.
- All investigations must be conducted in accordance with prevailing standards of care for drilling in dams/levees, and for environmental protection.
- Even the investigatory program may require a certain enhanced level of instrumentation monitoring during its implementation.

3.1.2 *Geotechnical Reports*

- Many different types of Reports can be produced on a project including:
 - Geotechnical Data Report (GDR),
 - Geotechnical Interpretive Report (GIR),
 - Geotechnical Baseline Report (GBR),
 - Geotechnical Design Basis Report (GDBR).
- It is essential that at least the GDR, GIR and GDBR are shared with all bidders, in full. GBR's are relatively uncommon outside the tunneling industry, and have very well-defined contractual and legal significance. The goals of these Reports, considered together, must:
 - allow development and understanding of an accurate hydrogeological model,
 - permit the Engineer-of-Record to design a responsive cutoff,
 - ensure that all bidders are on a "level playing field" when preparing their submittals,
 - clearly identify areas of particular geotechnical construction or performance risk,
 - permit the implementation of an appropriate geotechnical plan to monitor conditions before, during and after construction.

3.1.3 *General Principles of Cutoff Wall Design*

- Plan Location: A cutoff is typically located on the centerline of the embankment (for access reasons), or on upstream slope (to save footage and to ensure tie-in to sloping cores).
- Length: Determined by flow analysis to ensure minimal "end around" seepage. Most cutoffs actually tie-in to existing concrete structures, such as spillways or powerhouses. Their far end typically is determined by the geology and topography of the site (i.e., width of abutment).
- Width: The minimum continuous width (typically 0.3 to 0.6 m) should primarily be determined by the depth of the wall, the variability of the geology, the composition of the wall, and its performance requirements. Note that a cutoff wall does not have to be perfectly vertical to satisfy its design function: it can "ripple" provided the minimum inter-element overlap thickness is satisfied.
- Depth: The terminal elevation of the toe must be chosen to reflect the geological conditions and the design concept of the wall:
 - a "full depth" cutoff into effectively impermeable rock; or

- a “partial depth” (or “floating”) cutoff, to reduce (not eliminate) seepage and/or to prevent internal erosion. Such walls are often constructed through previously installed grout curtains (minimum 2 rows), intended to investigate the ground, pretreat voids to prevent sudden slurry loss; and grout to say < 3 Lu the rock mass under and around the wall in “clean fissure” conditions. This is the concept of the “composite wall” [6].
- Material Properties:
 - In-situ permeability (especially at joints) must be established, and verified. It is typically $\leq 10^{-8}$ m/s for materials, but 1 Lu for joints (i.e., approximately 1×10^{-7} m/s).
 - Strength and deformability must reflect the project conditions (e.g., plastic concrete vs structural concrete). All materials must be non-erodible in service.
 - Homogeneity must be emphasized, e.g., no inclusions of native ground or bentonite slurry, no segregation of the backfill, no contamination of the joints (or the toe) with slurry.
 - Durability/chemical compatibility must be addressed, but is typically not a problem.

3.1.4 Risk and Performance Considerations

- In dam safety considerations, Risk = Probability x Consequence.
- Risk is to be assessed in Potential Failure Mode Analysis sessions (PFMA).
- The individual PFM's, appropriately prioritized, must drive the remedial requirements and the instrumentation requirements.
- The performance of the cutoff and the existing structure must be measured during construction, and after construction. Specific project goals must be set and verified, e.g.:
 - reduction in seepage,
 - acceptable piezometric performance,
 - elimination of other “signs of distress” (e.g., settlements, sinkholes, muddy flows, boils).
- The evaluation of risk may dictate the sequencing and prioritization of the work and the permissible remedial techniques.

3.1.5 Durability of Walls

- The actual backfill materials must be durable. This will be proved by laboratory testing (“pinhole erosion”), quality of construction, and conditions of curing and service.
- There may be some evidence of cracking in old diaphragm walls, but the case is not proven. Newer walls have intense in-situ verification and superior long-term performance monitoring.
- Desiccation cracking may be a concern in embankments where the upper part may be above water level for most of its service life. However, the typical cross-sectional shape of an embankment is favorable (i.e., very broad).

3.2. CONSTRUCTION

- Each Contractor has its own particular mentality and preferences for means and methods, as well as for equipment. Each project's construction details must therefore be evaluated on this basis, with the prime concern being the safety of the dam during construction.
- A proper, stable, working platform (concreted if possible) is essential for a host of reasons, ranging from personnel safety to enhancing productivity.
- Some cutoff walls involve extensive pregrouting such as in the "Composite Wall" concept [6]. Such grouting must be conducted by an experienced and knowledgeable Contractor who may not necessarily be the same business entity as the cutoff wall Contractor. Insufficient or ineffective grouting may create dire problems to subsequent cutoff wall quality and schedule.
- "Technique Demonstration Areas" – thoroughly assessed – are invariably of great value to all the project's stakeholders.
- Time is well spent up front in building high quality, weatherproofed bentonite and concrete storage and batching facilities, and maintenance shops.
- Development of mix designs and their approval by the Owner should not be allowed to negatively impact schedule and should be given high priority during the site mobilization phase.
- All preconstruction permits, etc., must be in place prior to site mobilization.
- Ensure that all equipment is maintained regularly, and that all instrumentation is frequently recalibrated (if necessary).
- Individual cutoff wall elements, be they diaphragm wall panels, or secant piles, should be sized to minimize the number of inter-element joints, consistent, however, with dam safety concerns.

3.3. QA/QC AND VERIFICATION

- Details must be linked directly to the design intent and the project specifications, regulatory requirements, and to the actual construction techniques adopted by the Contractor.
- Key elements promoting success include:
 - Clear and complete contract specifications and drawings;
 - Appropriate organizational structure and qualified personnel;
 - Good communication protocols;
 - Cooperation from all parties (Owner, Engineers and Contractors);
 - Diligent implementation of the Quality Plan.
- A comprehensive, formal Quality Control Implementation Plan is essential, and the effort needed for the drafting and implementation of this Plan should not be underestimated by the Contractor. This project-specific plan must address, as a minimum:
 - Site organization charts showing responsibilities, lines of communication and levels of authority of project personnel from all stakeholders;

- Setting out methods and tolerances;
 - Bentonite slurry properties, production and testing;
 - Wall verticality and panel overlap (by at least 2 independent methods);
 - Wall tolerances;
 - Joint cleanliness criteria;
 - Concrete materials, batching, placement and testing;
 - Coring and in-situ permeability testing (and the use of an Optical Televiewer);
 - Management and communication of data and records (real time, and archived);
 - The development and implementation of a Joint Instrumentation Monitoring Plan (JIMP), between the Owner and Contractor.
- While an essential element of the Quality Plan is timely and accurate transmittal of information, the Plan must be developed and managed by an Engineer or Geologist, and not an IT Specialist in Data Management Systems.

3.4. INSTRUMENTATION AND PERFORMANCE MONITORING

- Prime types are piezometers, settlement gages, inclinometers, seismographs and weirs.
- Data loggers (“trolls”) can detect suspended sediments, change in pH, and temperature in seepages. Real time data transmission is preferable.
- Instrumentation adequacy must be audited, and supplemented if necessary, well in advance of construction (“baselining”).
- Location, intensity, and responsibility during construction must be governed by the JIMP.
- Monitoring must be continued after construction, with clear guidelines for identifying and acting upon Threshold and Action Levels.
- Long-term performance trends should be published in the technical community.

3.5. DEVELOPMENT OF CONTRACT DOCUMENTS AND CONTRACTUAL ARRANGEMENTS

- Performance-based specifications are optimal, and the fundamental performance goals must be clearly and consistently stated.
- Partnering must be implemented rigorously, and with total commitment at all levels in each stakeholder.

- Contractual risks must be allocated fairly, with the Owner being responsible for the site conditions and for the potential impacts and benefits of any previous remediations (e.g., by pregrouting) on the project. Risks to the Owner can be managed in many ways:
 - Ensure all available site-specific data are made available at bid stage;
 - Engage an appropriately qualified, experienced and resourced Design Engineer and Board of Consultants;
 - Clearly define respective roles, responsibilities, and duties, especially for site inspection staff;
 - Select a “Best Value” as opposed to “Low Bid” basis for Contractor selection;
 - Insist on a “Partnering” environment;
 - Select a qualified and experienced Contractor with appropriate human and mechanical resources;
 - Encourage the bidders, via Performance Specifications, to bring their own ideas and expertise to the project;
 - Ensure modifications are issued quickly, and be sympathetic to requests for bid extensions;
 - Allow budget for adequate short- and long-term instrumentation.
- There must be realistic expectations, such as that:
 - The project will satisfy the design intent;
 - The project will be designed and built to the current state of practice and to appropriate referenceable standards of care;
 - Project schedule is actually attainable (especially in “tight” projects with multiple trades);
 - The work will not cause damage or detriment to adjacent preexisting structures;
 - Claims are inevitable, and must be evaluated strictly on merit (often not the case when Construction Managers operating on very small margins are involved).
- The principles of “Early Contractor Involvement” should be applied whenever feasible, and especially on particularly challenging projects, technically or schedule-wise.

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SUMMARY

Twenty-seven case histories of major remedial cutoff walls have been reviewed. These cutoffs (excavate and replace methods only) have been installed through existing embankment dams and deep into usually karstic conditions to counteract the dangers to dam safety created by escalating seepage rates and velocities. "Lessons learned" are presented relating to design considerations, construction, QA/QC, instrumentation and development of contract documents.

Vingt-sept études de cas de réhabilitation de grande envergure des parois moulée ont été vérifiées. Ces parois (excavation et méthodes de remplacement seulement) ont été installées à travers des barrages en remblai existants et en profondeur en milieu karstique afin de contrer les risques en lien avec la sécurité des barrages créé par l'augmentation des taux et des vitesses des infiltrations. Les « leçons apprises » présentées concernent la conception, la construction, l'assurance qualité et contrôle de la qualité, l'instrumentation et la rédaction des documents contractuels.

KEYWORDS

Construction method, core wall, cutoff wall, diaphragm wall, embankment dam, foundation, internal erosion, karst, leakage, piping, rehabilitation.

Methode de construction, écran interne, mur parafouille, paroi moulée, barrage en remblai, fondation, erosion interne, karst, fuite, renard, rehabilitation.