

SAVING INSTITUTIONAL MEMORY AND THE EXTRAORDINARY COST-EFFECTIVENESS OF PROJECT DATABASES

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ABSTRACT

There is a well known adage to the effect that “those who ignore the lessons of history are condemned to repeat the same mistakes.” This is particularly relevant in the current period of dam and levee rehabilitation. In theory, for every project completed during the last 50 years at least, there should be a full “as-built” package of information available for review: such dossiers are extremely important sources of information when planning and undertaking subsequent repairs and modifications. Construction records, particularly grouting logs, can provide invaluable insights for focusing investigative or remediation programs.

However, the completeness of such project reporting is often compromised due to transfer of key personnel to the “next” project, or simply, misplacing of the physical evidence, especially after these personnel have retired. The information contained in contemporary “lessons learned” reports will usually provide clear indications of the cause of the problems which may subsequently develop. Such reports can highlight, with the benefit of hindsight, geological features improperly treated, design assumptions no longer consistent with current practice, and defects in construction. When “lessons learned” reports are complete and accessible, their information may allow contemporary engineers to justify not having to spend large sums of money on field research, or having to devote countless hours to “alternatives analysis.” They can therefore be extremely cost-effective for the owner.

There are two ways in which this historical value can be mined: by industry-wide reviews of specific technology applications, and through project-specific studies of historical records. In recent years the author has compiled two comprehensive databases relating to North American dam rehabilitation — one dealing with prestressed rock anchors, the other dealing with seepage cut-offs. The manner of their funding and execution, and their findings are summarized in this paper. The paper also illustrates how careful appraisal of such reports can prove invaluable in helping to understand current phenomena and to, therefore, optimize design time and effort.

Given the demonstrated value of even partial project documentation, supervising engineers and owners should make every effort and provide the resources to assure that it is comprehensive, securely archived, and readily accessible.

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INTRODUCTION

Most of the work we currently conduct in the dam and levee arenas is associated with reevaluation and reanalysis, leading where appropriate to some type of remediation, retrofit or upgrading. Such reevaluation and reanalysis projects progress especially efficiently and responsively when there is available for study a comprehensive collection of historical data and records. This collection would include:

- the original site investigation information;
- the original design memorandum or report;
- the original plans and specifications;
- the original construction photographs;
- the original project correspondence;
- the original foundation mapping records;
- the original construction records (and in particular anything relating to the foundation conditions, including any drilling and grouting if conducted);
- the “as-built” construction drawings;
- the contemporary QA/QC reports and test data;
- post-construction instrumentation data and other field observations;
- post-construction reevaluations and remediations where and when conducted;
- changes to the operational details of the dam and its reservoir;
- technical papers published in professional circles relating to the project.

In an ideal world, researchers would have available for interview and insight personnel who were involved in the original construction or in the subsequent performance monitoring or remediations.

Rarely, in the real world, do all these pieces fall into place together. Original records may not have been as detailed as those of contemporary practice. More often, such records have been mislaid, or destroyed, as owners change office locations, undergo corporate buyouts or lose or transfer key personnel before full documentation is completed. Many dams have surprisingly light levels of monitoring and instrumentation, and reading frequencies have often been extended in the face of budget pressures. Economic considerations will also have compromised an owner’s intent to conduct vital and timely reevaluations and modifications, especially in the days before our current levels of mandatory inspections and also in years when our nation’s priorities were focused in other directions.

It is as rare to find a project without *any* historical or performance information, just as it is to uncover a project with a *full* complement of information. The vast majority of projects have partial and incomplete datasets and the projects which are more impoverished and challenging are those with none or very poor records of original construction (which cannot be recreated). These stand in contrast to those with light post-construction instrumentation (since new instrumentation can always be emplaced to begin a new baseline, albeit one which will be discontinuous from conditions that would have existed from first reservoir filling).

When existing dams are reevaluated, they typically are subjected to a Potential Failure Modes Analysis (PFMA): this has become our standard of care in the last few years. Identification of the potential failure modes inevitably leads to a recommendation to conduct new phases of studies, and to the call to install additional instrumentation to monitor these modes. It is also typically the case that the analytical studies need new site investigation programs to provide reliable input parameters. All of these initiatives — analytical studies (especially when related to complex seismic aspects), new or replacement instrumentation, and site investigation (by drilling and sampling and/or by geophysical or other indirect methods) — have the potential to become both lengthy and costly, especially when “potential” momentum has been generated by what could be interpreted as the more extravagant and sensational outputs of the PFMA process.

It is at such times that the value of the institutional memory should be leveraged. The time and resources devoted to recovering the historical records, and then sifting through them for insights and understanding are relatively inexpensive and quick. Furthermore, they are without exception a source of education and enlightenment for the younger engineers who are most frequently allocated to such research at the “ground level.”

While the need for the analytical studies, additional instrumentation and further site investigation is not to be challenged, the point is that their respective scopes can be optimized (and typically and significantly reduced) by “picking the bones” of the historical data. This can be implemented in two ways, or two levels:

- Industry-wide experiences can be consulted, and
- Project-specific records can be mined.

The following sections of this paper provide examples within the author’s particular fields of expertise and experiences of how each of these strategies can and have been adopted to the benefit of the project and all its stakeholders.

EXAMPLES OF PROJECT DATABASES

National Research Program on Rock Anchors for North American Dams

This Program was implemented during 2004-2006, and it culminated in the two companion papers by Bruce and Wolfhope at the Ground Anchorage Conference in London in 2007. The origins of this research project in fact lay in one actual dam remediation project in the late 1990’s: the owner of the dam under consideration for remediation with high capacity prestressed rock anchors required comfort via a table of relevant similar case histories that the technique was viable and relatively “commonplace.” Quickly, through a cursory scan of published information, both in the U.S. and elsewhere, the details of over 50 projects were compiled for review. The project went ahead, to be followed by several other anchoring projects for the same client (Forbes et al., 2005). Further impetus for the National Research Project lay in the value generated by a survey of the use of epoxy-coated strands in dam anchors, which was conducted for the Association of Drilled Shaft

Contractors (ADSC) to help determine the root cause(s) of certain difficulties which had been recorded, but not disseminated, for general knowledge (Bruce, 2002).

In attempting to put together funding for the ambitious National Research Program, two factors became apparent:

1. With one exception, no professional or trade association was in a position to contribute financially, although all professed “great interest” in being able to access the results, and expressed “good luck” sentiments to the potential researchers.
2. There was reluctance for *any* party to be “first in the pool”: all potential funding sources wanted to be reassured that they were not the first (and potentially only!) to contribute.

Eventually, funds were committed by two commercial entities, Boart Longyear and Sumiden, the former being interested in the market from the drilling point of view, the latter from the post-tensioning aspects. Furthermore, Sumiden, a U.S. subsidiary of a major Japanese multidisciplinary corporation, were keen to participate since the Japanese market in dam anchoring was just about to get underway. With these funds in place, the Industry Advancement Fund of ADSC then committed matching funds, believing that there was value to its membership in helping to produce such a study. In addition, of course, a great deal of effort was committed, without being billed for, by the staff of both the Principal Investigators’ companies.

Sources of information included a review of all published papers (and their reference lists), and direct contacts with industry participants (including tendon suppliers, contractors, consultants and owners). In this regard, the Investigators were often able to collect information on any given project from several sources, the most detailed and valuable being the tendon suppliers’ sales inventories and billings, the contractors’ shop drawings and “as-builts,” and less frequently, the engineers’ design memoranda and specifications.

As a consequence of all these studies, the following were compiled:

- A database of over 230 technical papers published on the subject between the early 1960’s and 2005, as shown in Figure 1.
- A compilation of all the successive Post Tensioning Institute (PTI) / Prestressed Concrete Institute (PCI) “Recommendation” documents governing design, construction and testing. As shown in Table 1, this proved particularly useful in illustrating the development of concepts and attitudes with time, especially with regard to the critical issues of corrosion protection, and stressing and testing.
- A database of over 400 separate anchor projects completed in North America between 1962 and 2004 of which about 70% could be regarded as very comprehensive records and a further 12% labeled as “partial” (Figure 2).

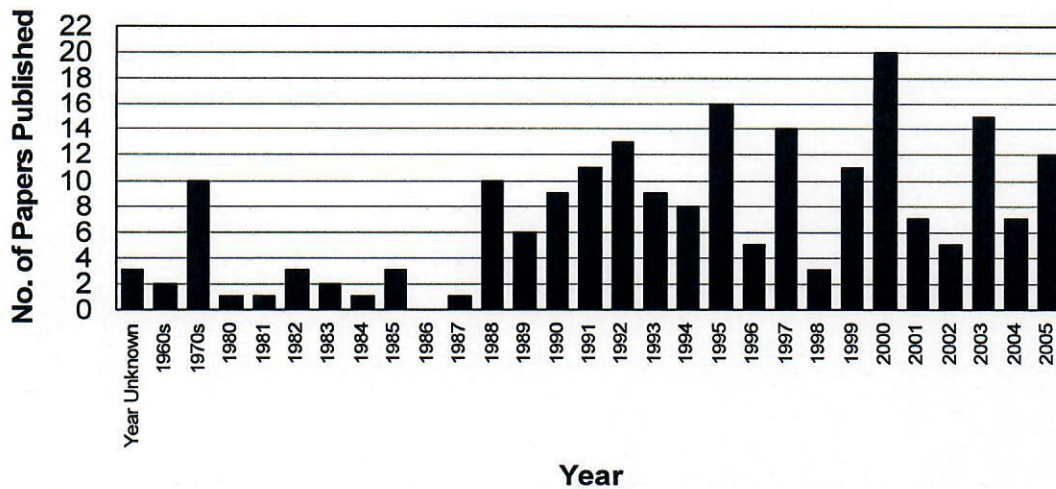
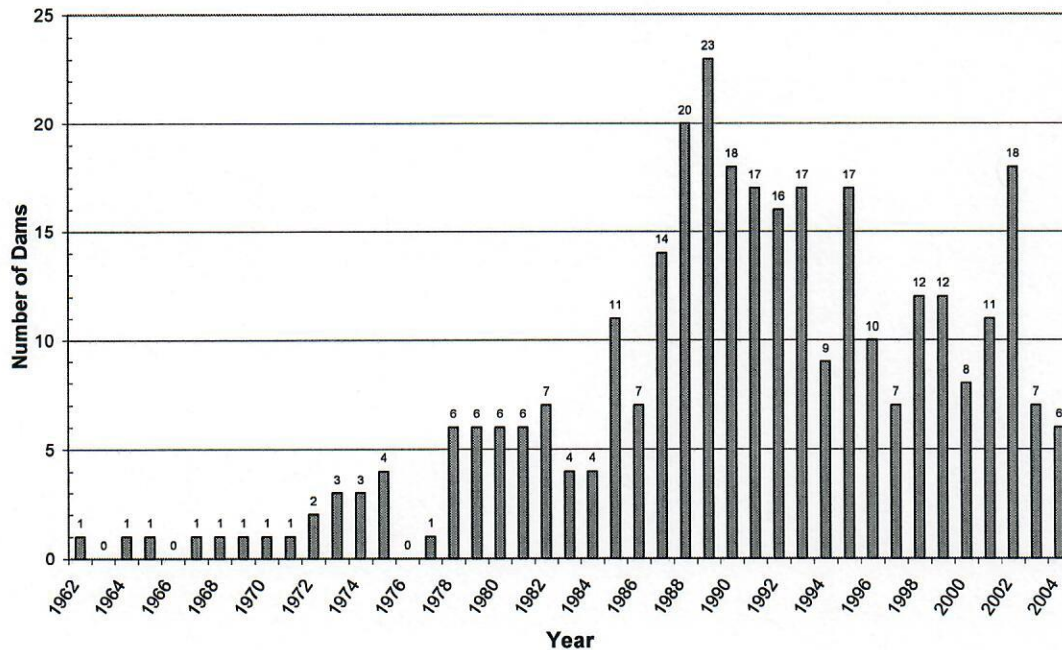


Figure 1. Numbers of technical papers on dam anchoring published per year (Bruce and Wolfhope, 2007).

Table 1. Number of pages in major sections of successive U.S. “Recommendations” documents (Bruce and Wolfhope, 2007).

ASPECT	1974	1980	1986	1996	2004
Materials	1	2	2	8	10
Site Investigation	0	1	1	1	2
Design	2	6 ½	6 ½	12+ Appendix on grout/strand bond,	14
Corrosion Protection	1	4	5	10	14
Construction	7	9	9	10	15
Stressing and Testing	1	6	8	17	18
Bibliography/References	0	1	1	1 ½	4
Applications	16	18	0	0	0
Recordkeeping	0	1	1	1 ½	1 ½
Specifications	0	1	1 ½	2	2
Epoxy-Coated Strand	0	0	Very minor reference,	Frequent reference but no separate section.	10 Separate sections.
TOTAL PAGES	32	57	41	70	98

Histogram of Dams Anchored - North America (1962-2004)



Notes: 1) Total Number of Dams Shown = 323

2) Does not include 70 anchor case studies where year anchored not reported or as yet ascertained.

Figure 2. Histogram of dams anchored by year (1962-2004)
(Bruce and Wolfhope, 2007).

There have been many benefits from this work which has been freely published and is in the public domain. These include:

- A unique illustration of the technical evolution of a specialty geotechnical construction technique over a relatively short period, and of the controlling factors behind it (e.g., early works were largely controlled by the post-tensioning companies, as in Europe or Australia, whereas from the 1980's onwards, the contractors drove the market in the U.S.).
- A basis for contractors from which to project market trends, i.e., the number and value of projects that are *likely* to be bid in the years to come.
- A basis for owners to access the probable status of the current functionality of their anchors. In other words, the reliability of the 60-70% of all known dam anchors installed before Type 1 corrosion protection ("double corrosion protection") was first defined in the 1996 "Recommendations" document of PTI, the de facto equivalent of a national standard. This issue is illustrated in [Figure 3](#).
- A basis for potential owners and designers to conduct a "reality check" on provisional design schemes and details, and to help them avoid falling into the trap of reinventing the wheel on any given project. Such traps may result in the projected costs for the anchoring being severely overestimated, thereby leading to the rejection of anchoring

as a solution and the adoption of a technically less attractive option which, of course, itself may be overpriced relative to an accurate anchoring cost estimate.

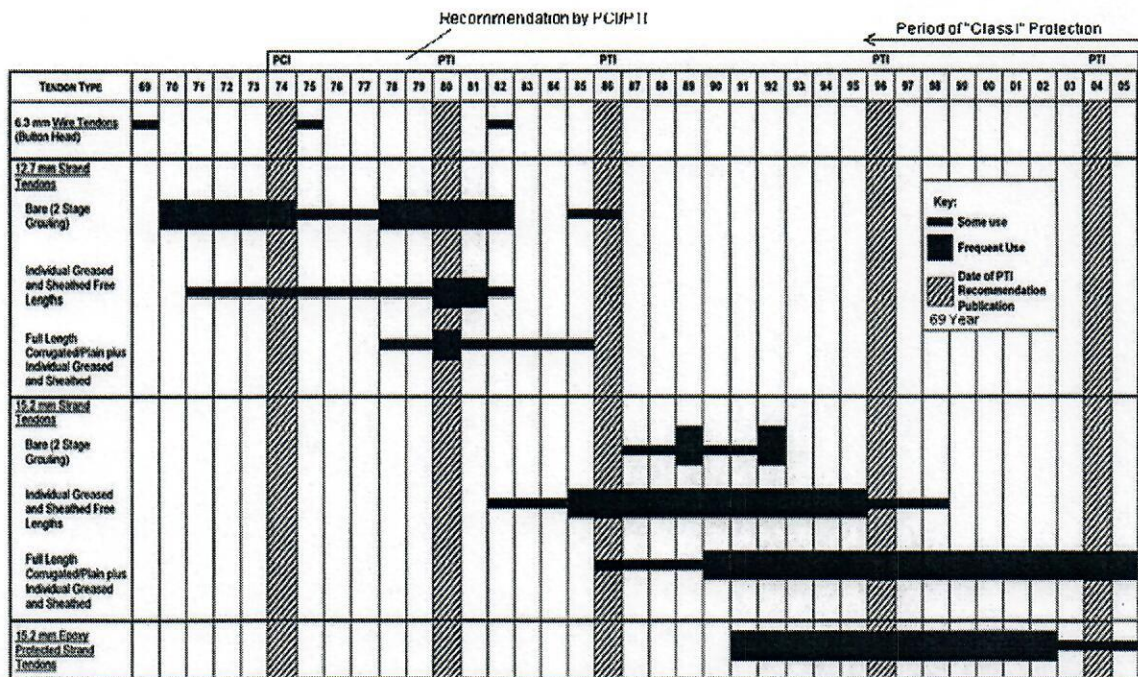


Figure 3. Illustrating how the types of corrosion protection have evolved (Bruce and Wolhope, 2007).

This is obviously not a comprehensive list of benefits but, for dam owners, it is ironic that arguably the most significant of the benefits of the study may in fact be the one which has greatest dam safety implications. The issue of the reliability of the majority of anchors installed before 1996 is absolutely critical, especially for those anchors installed in the 1960's and 1970's when the free length was commonly not protected by a sheathing (bond breaker) and was therefore fully bonded by secondary grout following stressing. Such anchors cannot be lift-off tested to determine the residual load, even assuming they could still have physically accessible anchor heads. Even when a residual free length was incorporated, unacceptable levels of corrosion protection still occurred on occasions (Heslin et al., 2009) leading to corrosion occurring from the onset with progressively more severe loss of load (Photograph 1).

The researchers found that some of the best documented case histories were in fact from the early anchor projects, especially those conducted for the U.S. Army Corps of Engineers (USACE). Close study of the details of these projects helps us to better understand the risk posed by tendon corrosion, on a project by project basis, since it has become clear that not all projects were built to the same standards of care or with the same construction concepts or details. This is a major challenge to the profession, which is shared by colleagues in other parts of the world. Without such a review of institutional knowledge, it is unlikely that this critical problem would have been raised or its extent quantified. Optimistically,

the details in the database will allow the site specific risk to be quantified, at least to a screening level.



Photograph 1. Water emerging from the free length of an improperly protected tendon subject to excess hydrostatic head (Heslin et al., 2009).

Review of Remedial Cutoffs for North American Dams

During 2005 and 2006 the author conducted, as an individual research initiative, a survey of existing dams in North America which had been remediated against seepage by use of some form of “positive” cutoff. The results were first published in 2006 (Bruce et al.). Information from the published literature was supplemented by unpublished reports and contractor’s “data sheets.” Eventually a total of 32 case histories was uncovered, of which relatively complete information was assembled for 23 of these projects, of the type illustrated in [Table 2](#). The data are displayed in different format in [Figure 4](#). For each case history, a “lessons learned” summary was developed.

This survey had shown that such cutoff projects had been conducted, more or less continuously, since 1975 using various construction techniques. The first publication of this work serendipitously coincided with the major upsurge in dam remedial projects in the mid-2000’s following the USACE’s portfolio assessment initiative after the Katrina disaster. The historical review therefore provided a basis for reflecting the capacity of industry to respond to the demands of the foreseen program: the implication was that the amount of new work foreseen over a 5-year period would be about the same as that conducted over the previous 30 years (about 6.3 million square feet of “concrete” cutoffs).

This challenge was not only to the capacity of contractors to provide appropriate levels of resources — especially human — but equally to the owners who had to find their own levels of resources — financial as well as human. This “owner’s problem” has proved particularly acute in certain regions which, for geological and historical reasons, are now responsible for simultaneous major rehabilitation projects.

Table 2. Details of 23 remedial dam cutoff projects which are well documented ("A List") (Bruce et al., 2006).

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	
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) • Feizer (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 (Production)	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.

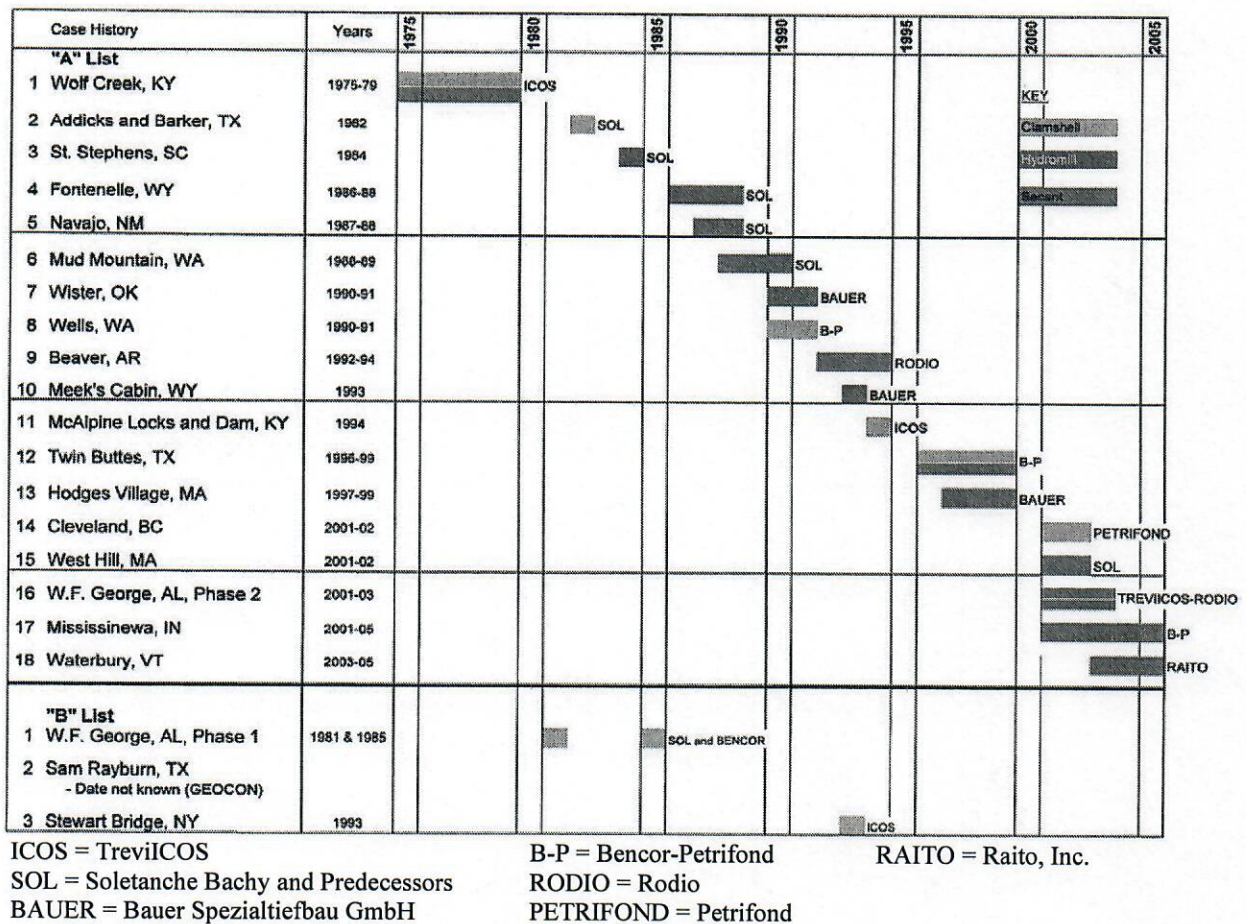


Figure 4. Project listing showing chronology, type and cutoff specialty contractor (Bruce 2007).

From the technical side, this review has provided planners with perspective about the capabilities of the specialty contractors, the depth limitations of each technique, how to overcome especially difficult ground conditions (e.g., karst) and the range and properties of cutoff wall “backfill” materials which have been used. It has also aided budget schedule estimating. This study has further helped in the development of related technical overviews, both by the current author (Bruce, 2009, and Bruce et al., 2010), and others (Rice and Duncan, 2010).

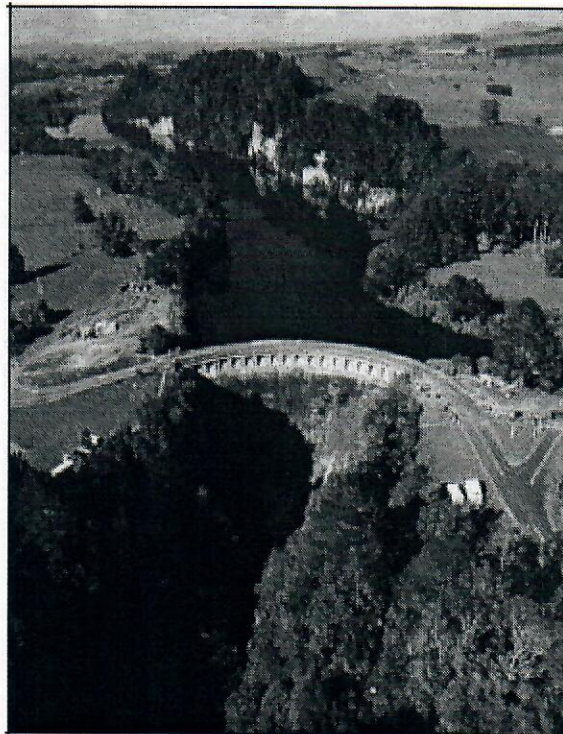
Finally, it is hoped that the 2006 overview will provide a historical baseline against which to compare the findings and achievements of the current wave of remediations when these are completed — and hopefully published — over the next few years.

EXAMPLE OF A PROJECT-SPECIFIC DATABASE

Arapuni Dam is a 64 m high curved concrete gravity structure of crest length 94 m. It sits on the Waikato River in the North Island of New Zealand and was completed in 1927 (Gillon and Bruce, 2003). A series of foundation leakage events had since occurred following first impoundment. These were related to piping within, and erosion of, the weak clay infilling the defects within the sheated volcanic ignimbrite rock foundation. What proved particularly puzzling for many years was that changes in seepage conditions often involved sudden and significant changes which could not be related to specific, external events, such as earthquakes.

In the case of Arapuni, there was an excellent and comprehensive collection of historical data including construction photographs, seepage measurements and details of numerous remedial efforts over the years. In addition, the genesis and lithology of the foundation was particularly well understood thanks to the input of an extremely experienced, local, professional geologist. All these sources contributed to the quick development of a robust hydrogeological model for the site which, in particular, identified that:

- Seepage in the foundation rock was isolated from the abutment seepage even though the valley is extremely narrow (Photograph 2).



Photograph 2. Arapuni Dam, New Zealand (Amos et al., 2008).

- There was no blanket grouting, curtain grouting or drainage curtain in the original dam construction. The remedial curtain constructed during a 1929-1932 lake lowering was,

in accordance with the U.S. practice of the day: a single row of vertical holes at 3 m centers. Furthermore, it was constructed *upstream* of the dam (Figure 5) and was not structurally connected to it, injection pressures were modest, grout mixes were unstable, and the curtain did not extend for the full depth of the permeable and problematic Ongatiti Ignimbrite sheet. However, the retrospective saving grace of the curtain was that it constituted what was basically a very intense site investigation in which the elevations of loss of drill water and “runaway” takes were meticulously recorded, allowing the locations and trends of the defects to be recognized.

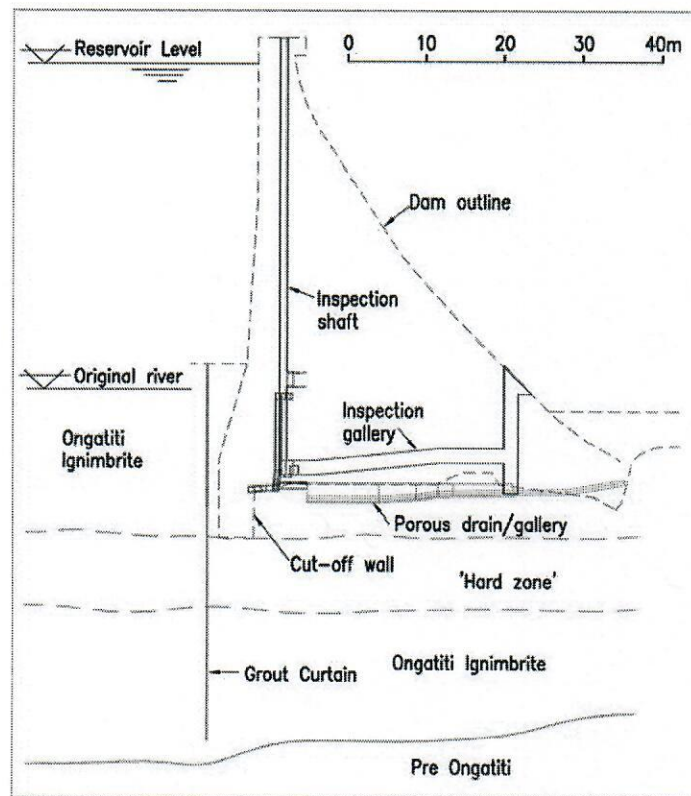


Figure 5. Cross section of Arapuni Dam looking west (Amos et al., 2008).

- These data, plus later site investigation holes specifically targeted as a result of historical and geological evaluations, allowed the identification of 4 sets of well defined families of defects striking under the dam (Figure 6). These were confirmed in their lateral and vertical extent by the focused site investigation program. The fissures ranged up to 80 mm in aperture and related to cooling (venting and contraction) of the ignimbrite after emplacement and were not tectonic in origin. Clay infill was generally present where the fracture existed: the infill was nontronite, an iron rich smectitic clay of very high moisture content and very low shear strength. It was therefore potentially erodible under hydraulic pressure. Where this fracture infill was not present, seepage pressures correlating to full reservoir level were measured in some areas of open joints under the dam.

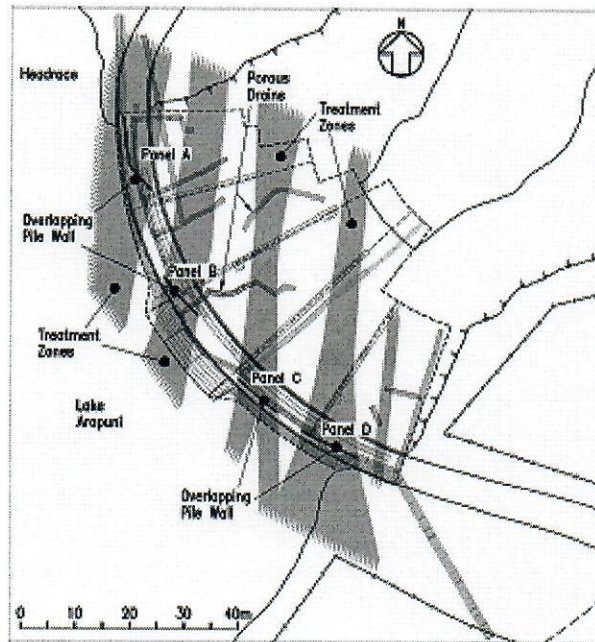


Figure 6. Plan of long-term seepage control remedial works, with cutoff walls, treatment zones and underdrain (Amos et al., 2008)

This model convinced the Engineer that the situation — based on seepage and piezometric observations — was extremely serious and had deteriorated rapidly between 1995 and 2001. The obvious and major fear was that there was a credible risk that sudden and massive seepage could occur from fissures daylighting downstream, as a result of accelerating piping. An interim, emergency grouting project was therefore instigated under the dam in late 2001 and was successful. With the situation stabilized, the design and construction of the definitive cutoff could then be conducted in a “targeted and cost-effective” manner (Amos et al., 2008) to the highest practical standards of quality and performance verification.

Further economic benefits accrued to the project from the fact that operation of the reservoir was not affected and electricity generation continued unabated throughout the works. No dam safety or environmental problems were recorded. Interestingly, the owner’s insurance premiums were reduced, substantially, after verification of the quality of the remediation.

CLOSING REMARKS

The author is currently involved in an external peer review function for the assessment, and eventual remediation, of a 1970’s dam in Texas. As is often the case given the topography in the lower part of that state, the flanking abutments are several miles in combined length. The PFMA process identified erosion of karstic features in the foundation limestone as being a plausible and prime threat to dam safety above certain reservoir elevations. Further site investigation studies were planned, with all parties acknowledging that a high degree of focus would be needed to ensure that the limited

investigation funds were not to be dissipated in the “general screening” type of approach, e.g., 1 hole regularly every 500 feet or so.

However, as-built records were located which included extremely detailed, hand-drawn, records of the original grout curtain which, of course, had been constructed in the fashion of the day. In many ways, this mirrors the Arapuni experience: a curtain whose prime value now resides in its unanticipated status as an excellent site investigation. Regardless of the efficiency with which the grouting was conducted, or how it subsequently performed, it provides a real time, indisputable record of the location of distinct karstic features. It also confirmed that large stretches of the foundation were “tight” and therefore not capable of being eroded or piped. Plans have been made, therefore, to focus the attention of the proposed investigations on the zones identified by the historical grouting records. The investment in the historical analysis is minimal compared to the potential benefits to the project resulting from a meaningful site investigation, followed by a focused, localized, remedial effort.

Wolf Creek Dam, in Kentucky, is currently undergoing a massive seepage remediation involving almost one million square feet of concrete diaphragm wall demanding state of the art construction techniques. Previous remedial work conducted on this dam between 1968 and 1979 involved extensive drilling and grouting, and the nation’s first concrete cutoff for an existing embankment dam. (TVA had in fact attempted such a cutoff under an existing concrete structure in the 1940’s.) Prior to preparing detailed designs for the current retrofit, the owner commissioned a comprehensive database of all sources of information on the complex foundation conditions, ranging from extremely insightful photographs of foundation excavation exposures to a compilation of the various phases of remedial data (Spencer, 2006). This database was equally valuable to the prospective bidders of the current remediation, in that it helped them anticipate construction risks and optimize their selection of means, methods and foreseen productivities. During the current construction, this database is regularly referred to by the various stakeholders, especially when construction is impinging on more “difficult” areas of the foundation.

A major program of seepage remediation is currently being contemplated for a surprisingly high, concrete faced rockfill dam in Kentucky which dates from the 1920’s. The initial fear arising from the relatively rapid, recent rise in total seepage rates was that the karstic limestone underlying and abutting the dam had reached a Wolf Creek degree of internal erosion. The current consultants, however, have located a series of dam inspection and evaluation reports extending back to 1944: one particular grouting campaign is described as “likened to saturation bombing as compared with precision bombing.” The records and observations are as insightful as they are meticulous. Pending the outcome of the current focused verification phase of site investigation, it would seem most likely, however, that the major component of flow is occurring *through the dam* (and so does not pose a dam safety threat) as opposed to *through the foundation or abutment* (which would most certainly be a serious condition). The repair of the dam itself will be much simpler and cheaper than the potential construction of a cutoff in the limestone. Such an outcome would of course be welcome news to the owner – but not the brotherhood of specialty geotechnical contractors!

The point of these examples is to illustrate again the extraordinary benefits that can accrue to a project as a result of industry- and project-specific databases being available during the investigation, design and construction phases of remediations. Historical records are “gold mines” of information from which priceless “clues” can be extracted — even while we may now disagree with the original design and construction approaches. To this end, supervising engineers and owners should make every effort and provide the necessary resources to assure that historical data analyses, both technique- and project-specific, are sponsored and the results are securely archived and rendered accessible.

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