Rock Anchors for Dams: National Research Project: The (Semi) Final Results of the Phase 1 Study

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ABSTRACT
This paper provides an update on the findings of the National Research Project on Rock Anchors for Dams (Phase 1). It focuses on three tasks: (1) an analysis of the evolution of anchor practice as illustrated by five successive sets of "Recommendations" published by PCI/PTI; (2) the compilation of a bibliography of technical papers that have been published on North American post-tensioned rock anchor practice; and (3) the compilation of technical details of each of the dams that have been anchored in North America, dating back to 1964.

RÉSUMÉ
Cet article fait le point sur les résultats du Projet national de recherche sur les tirants d'ancrage pour barrages (Phase 1). Il se penche sur trois points spécifiques : (1) l'analyse de l'usage des tirants d'ancrage qui a évolué parallèlement aux cinq séries consécutives de « Recommandations » publiées par PCI/PTI; (2) la compilation d'une bibliographie d'articles techniques ayant comme sujet l'utilisation en Amérique du Nord des tirants d'ancrage post-tensionnés et (3) la compilation de données techniques pour chaque barrage nord-américain qui a utilisé des tirants d'ancrage depuis 1964.

1. INTRODUCTION

The current authors have published a number of papers detailing progress in the various tasks under the National Research Project on Rock Anchors (Bruce and Wolfhope, 2005; Bruce and Wolfhope, 2006; National Rock Anchor Research Project, 2005). In the course of conducting this research, they have benefited greatly from the input provided by members of the Association of State Dam Safety Officials and the Canadian Dam Association, and again extend their thanks and appreciation. The schedule for completion of Phase 1 of the Project has extended as the scope of the work has expanded, and the awareness of the value of the works by owners, consultants, contractors, and suppliers alike has heightened.

Of the three Phase 1 tasks, two are essentially complete, and the third is nearing completion. Therefore this paper cannot constitute the "final report" on all the tasks. Rather it provides synopses of the completed work relating to (1) an evaluation of the historical evolution of anchor practice as seen through the pages of the five successive editions of the "Recommendations," published by the Post Tensioning Institute (1980, 1986, 1996, and 2004) and by the Prestressed Concrete Institute (1974) and (2) the generation of a bibliography of dam anchor papers relating to North American practice. The paper also provides the current statistics on the third task, namely a compendium of data on every dam anchored to date in North America. This task is currently incomplete, since information still has to be obtained (or discovered!) on a significant number of projects.

2. EVOLUTION OF PRACTICE

2.1 General Statement

Current research indicates that the first U.S. dams to be stabilized by high capacity prestressed rock anchors were the John Hollis Bankhead Lock and Dam, Alabama in 1965 and the Little Goose Locks and Dam, Washington in 1968. These projects were completed for the U.S. Army Corps of Engineers who had sufficient confidence in the technology (and, presumably, a pressing need for it!) that they were the sponsor for most of the half dozen or so similar applications in the six years that followed. The U.S. Bureau of Reclamation began using anchors to stabilize appurtenant structures at dams in 1967. The Montana Power Company was also an early proponent. In those days, the technology was largely driven by the post tensioning specialists, employing the same principles and materials such as used in prestressed/post tensioned structural elements for new buildings and bridges. The "geotechnical" inputs, i.e., the drilling and grouting activities, were typically subcontracted to drilling contractors specializing in site investigation and dam grouting in the west, and to "tieback" contractors in the east.

Recognizing the need for some type of national guidance and uniformity, the Post Tensioning Division of the Prestressed Concrete Institute (PCI) formed an adhoc committee which published, in 1974, a 32-page document entitled "Tentative Recommendations for Prestressed Rock and Soil Anchors." It is interesting to note that half of the document comprised an appendix of annotated project photographs intended to illustrate and presumably promote anchor applications, including dam anchors at Libby Dam, Montana, and Ocoee Dam, Tennessee.

After publication of its document, the Post Tensioning Division of PCI left to form the Post Tensioning Institute (PTI) in 1976. Successive editions of "recommendations" were issued in 1980, 1986, 1996 and 2004. As general perspective to the development of concepts, Table 1 provides an analysis of the relative and absolute sizes of the major sections in each successive edition. It is immediately obvious that the original documents were heavy on "applications" – in an attempt to promote usage – while the most recent edition provides very detailed guidance (and commentary) on the "big five") in particular (i.e., Materials, Design, Corrosion Protection, Construction, and Stressing/Testing).

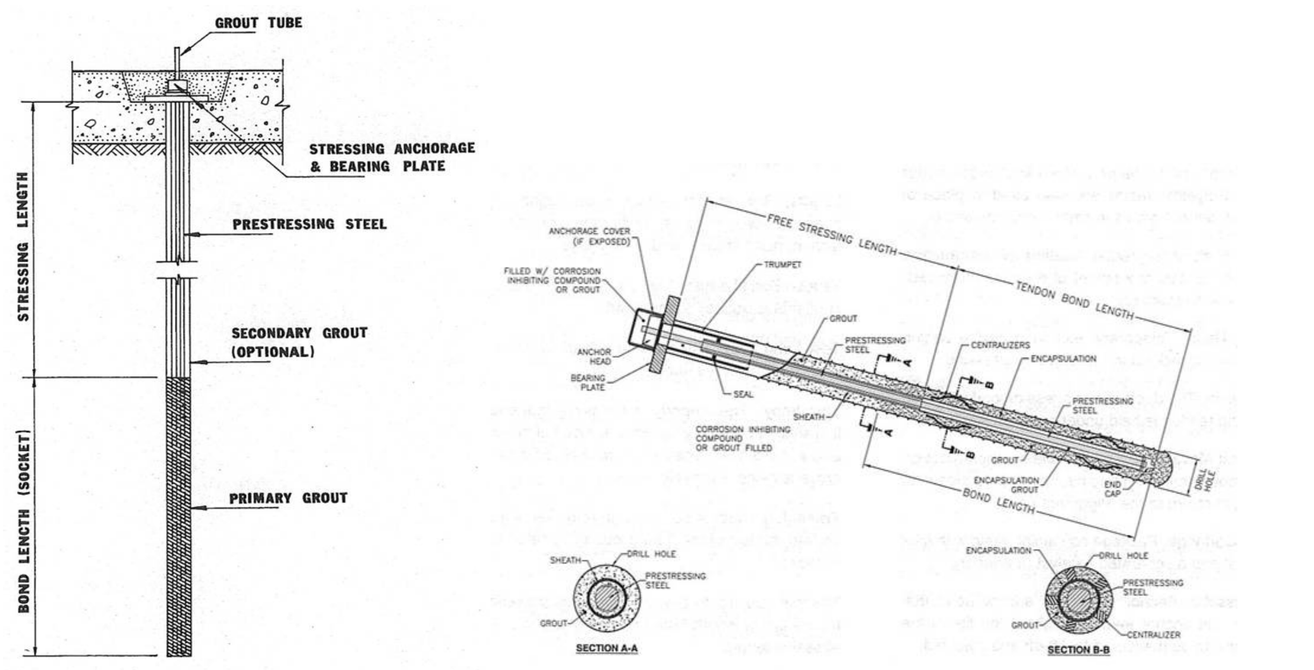
A further introductory message can be read by comparing the simplicity of a "typical" 1974 anchor (Figure 1a) with the sophistication of its 2004 counterpart (Figure 1b).

2.2 Detailed Comparison by Topic

The structure of each successive edition has changed in the same way that the content has, although there are comparatively few structural differences between the 1996 and 2004 versions. The following comparison therefore is based on the structure of the 2004 version.

Table 1. Number of Pages in Major Sections of the "Recommendations".

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



(a) (b)

Figure 1a. (a) Rock anchor terminology and components (PCI, 1974) and (b) Typical components of an anchor (PTI, 2004)

- Scope and Definitions (Chapters 1 and 2)
  The scope has remained relatively constant, and focuses on the anchors themselves (as components) as opposed to the analysis and design of the overall anchored system. A total of 72 technical terms are now defined, which represents a major expansion even over the 1996 edition: the first edition has 24 definitions, most of which, incidentally, remain valid and little changed.

- Specifications, Responsibilities and Submittals (Chapter 3)
  Whereas 1974 provided no insight into specifications and responsibilities, certain records were to be maintained on the grouting operations. By 1980, however, specifications had been addressed, reflecting the need to tailor procurement processes to "experienced" contractors, "thoroughly experienced" and match the innovation of the technique with alternative procurements methods. It is notable that the three types of specification outlined in 1980 (namely open, performance and closed) have endured, although "closed" is now referred to as "prescriptive." Building on a 1996 innovation, the responsibilities to be discharged during a project — regardless of type of specification — were summarized in 2004 as shown in Table 2. Clear guidance is also provided on the content of preconstruction submittals and as-built records. The former also include the requirement for a Construction Quality Plan. Emphasis remains on the need for "specialized equipment, knowledge, techniques and expert workmanship" and for "thoroughly experienced" contractors. The obvious, but often ignored, benefit of "clear communication and close cooperation," especially in the start up phase, is underlined.

Table 2. Tasks and responsibilities to be allocated for anchor works (PTI, 2004).

1.	Site investigation, geotechnical investigation and interpretation, site survey and potential work restrictions.
2.	Decision to use an anchor system, requirements for a pre-contract testing program, type of specification and procurement method, and contractor prequalification.
3.	Obtaining easements, permits, permissions.
4.	Overall scope of the work, design of the anchored structure, and definition of safety factors.
5.	Definition of service life (temporary or permanent) and required degree of corrosion protection.
6.	Anchor spacing and orientation, minimum total anchor length, free anchor length and anchor load.
7.	Anchor components and details.
8.	Determination of bond length.
9.	Details of water pressure testing, consolidation grouting and re-drilling of drill holes
10.	Details of corrosion protection.
11.	Type and number of tests.
12.	Evaluation of test results.
13.	Construction methods.
14.	Requirements for QA/QC Program.
15.	Supervision of the work.
16.	Maintenance and long-term monitoring.

- Anchor Materials (Chapter 4)
  The 1974 document very briefly refers to wires, strand, and bars, and to protective sheathing. In stark contrast, the current version has built to 10 pages providing definitive detail on materials used in each of the 10 major anchor components, with particular emphasis placed on steel, corrosion-inhibiting compounds, sheathings and grouts (cementitious and polyester). Strong cross-reference to relevant ASTM standards is provided as a direct guide to specification drafters.

- Site Investigation (Included in Chapter 6 – Design)
  Not referred to in 1974, recommended first in 1980 and completely revised and expanded in 1996 and 2004, this issue now provides clear guidance on the goals and details of a site investigation program. "Minimum requirements" are recommended. However, this remains an area where the anchor specialist often has less "leverage" to influence since the costs associated with such programs typically exercise strong control over the scope actually permitted by the owner.

- Corrosion and Corrosion Protection (Chapter 5)
  Prior to 1996, European specialists found fault with the PTI recommendations insofar as they perceived U.S. practice to be somewhat lax — not to say deficient — with respect to attitudes towards corrosion and corrosion protection. However justified this criticism may have been when considering the entirety of anchor applications including relatively high capacity tiebacks in urban soil conditions, it was probably overstated when the particular issue of high capacity anchors for dam stabilization could be considered in isolation. For a variety of logical, historical reasons, by far the greatest percentage of U.S. dams had been founded on "good rock" foundations, typically on sites which had also been grouted to a certain intensity during initial construction. U.S. practitioners were therefore comfortable that the coincidence of rock masses with low permeabilities (natural or influenced) with appropriate standards of care and workmanship during construction would assure acceptable long-term performance with respect to corrosion resistance. The historical record supports this position, even if there has been a distinct element of "grace of God" in the supporting logic, and a marked degree of internal confusion as to what "single" and "double" corrosion protection really meant. In 1974, "permanent" was synonymous with a 3-year service life, this life varying to 18 months in 1980 (when a significant advance was made in the recommendations) to 24 months in 1996 and 2004. Permanent, it would seem, is subject to change.

  There is no question that one of the main concerns frequently expressed by potential users of rock anchors in dams was (and still is) concern over corrosion protection. This concern was specifically addressed in the 1980 and 1996 recommendations in particular. By 2004 the PTI committee was in the comfortable position of simply having to install relatively minor modifications and enhancements to the structure radically introduced in 1996.

  This evolution is particularly clearly illustrated in the details of the individual case histories analyzed in Section 4 of this paper. The earliest anchors (typically multi-wire tendons) had no protection in either the bond or free lengths and were therefore two-stage grouted. Prior to the mid 1980s, it was still common practice to have the tendons (mainly strands but with sheathing on the free length) installed with no bond zone protection. Thereafter an increasing trend was noted to providing a corrugated protection but only over the bond zone and tying into the free length protection. By the early 1990s, epoxy coated strand and/or full length corrugated protection became more common, a trend strengthened by the 1996 Recommendations.

The researchers of the National Research Project so far confirm the following statement made in the 2004 Recommendations: "Permanent anchors have been routinely installed in North America since the mid 1960's. They continue to perform well in a variety of environments, applications and ground conditions." No failures have been found which can be directly ascribed to corrosion protection failure.

- Design (Chapter 6)
  Judging from the relatively short and simplistic coverage of this aspect in 1974, it is fair to say that not much was really then *known* of the subject. Core drilling was considered absolutely necessary and preproduction pullout tests were "strongly recommended." However, two enduring issues were faced:
  - The safety factor (on grout-rock bond) "should range from 1.5 to 2.5", with grout/steel bond not normally governing.
  - A table of "typical (ultimate) bond stresses" was issued as guidance to designers.
    Today even despite superior and often demonstrated knowledge of load transfer mechanisms (i.e., the issue of bond stresses NOT being uniform), the same philosophy prevails:
  - The safety factor (reflecting, of course, the criticality of the project, rock variability and installation procedures) is normally 2 or more.
  - A table of "average ultimate" bond stresses presented, which is basically identical except for typos, to the 1974 table.
    However, the current edition does provide very detailed guidance on critical design aspects, including allowable tendon stresses; minimum free and bond lengths; factors influencing rock/grout bond stress development; anchor spacing; grout cover/strand spacing; and grout mix design.

- Construction (Chapter 7)
  As noted above, there was a strong bias in the 1974 document towards construction, largely, it may be assumed, because practice far led theory. Furthermore, much of what was described in 1974 remains valid, especially with respect to issues relating to grouts, grouting and tendon placement. Certain features, such as a reliance on core drilling, the use of a "fixed anchorage" at the lower end of multistrand tendons, and specific water take criteria to determine the need for "consolidation grouting" are, however, no longer valid.
  The 2004 version expanded upon the 1996 guidance, itself a radical improvement over its two immediate predecessors, and is strongly permeated by an emphasis on quality control assurance. For example, practical recommendations are provided on the fabrication of tendons (including the pregrouting of encapsulations) and storage handling and insertion drilling methods are best "left to the discretion of the contractor, wherever possible," although specifications should clearly spell out what is not acceptable or permissible. In rock, rotary percussion is favored, and the drilling tolerance for deviation of 2º is "routinely achievable," while smaller tolerances may be difficult to achieve to measure. Holes open for longer than 8 to 12 hours should be recleaned prior to tendon insertion and grouting.

  The acceptance criterion for water pressure testing is adjusted to 10.3 liters in 10 minutes at 0.035 MPa for the entire hole. Technical background is provided on the selection of this threshold (based on fissure flow theory). Holes with artesian or flowing water are to be grouted and redrilled prior to water pressure testing. The pregrout (generally WCR = 0.5 to 1.0) is to be redrilled when it is weaker than the surrounding rock. When corrugated sheathing is preplaced, the water test should be conducted on it, prior to any grouting.

  The treatment of grouting is considerably expanded and features a new decision tree to guide in the selection of appropriate levels of QC programs. Holes are to be grouted in a continuous operation not to exceed 1 hour, with grouts batched to within 5% component accuracy. The value of testing grout consistency by use of specific gravity measurements is illustrated. Special care is needed when grouting large corrugated sheaths; multiple stages may be required to avoid flotation or distortion, and the cutting of "windows" (to equalize pressures) is strictly prohibited.

- Stressing, Load Testing and Acceptance (Chapter 8)
  Given the professional experience and background of the drafting committee, it is surprising, in retrospect, to note the very simplistic contents of the 1974 document:
  - "proof test" every anchor to ≥ 115% "transfer" load (to maximum 80% GUTS),
  - hold for up to 15 minutes (but no creep criterion is given),
  - lock-off at 50 to 70% GUTS,
  - alignment load = 10% of Test Load, with movement only apparently recorded at this Test Load (115 to 150% transfer load). "If measured and calculated elongations disagree by more than 10%, an investigation shall be made to determine the source of the discrepancy,"
  - lift-off test may be instructed by the Engineer "as soon as 24 hours after stressing."
    Despite significant advances in the 1980 and 1986 documents, reflecting heavily on European practice, significant technical flaws persisted until the completely rewritten 1996 version. The 2004 document was little changed in structure and content, the main highlights being as follows:
  - Practical advice is provided on preparatory and set up operations and on equipment and instrumentation including calibration requirements.

- Alignment Load can vary from 5 to 25% of Design Load and 10% is common. Otherwise, no preloading is permitted prior to testing. On long, multistrand tendons, a monojack is often used to set the Alignment Load, to ensure uniform initial loading of the strands.
- Maximum tendon stress is 80% F_{pu}.
- Preproduction ("disposable," test anchors, typically 1 to 3 in number), Performance and Proof Tests are defined, the latter two covering all production anchors.
- For Performance Testing, the first 2 or 3 anchors plus 2 to 5% of the remainder are selected. The test is a progressive cyclic loading sequence, typically to 1.33 times Working Load. A short (10 or 60 minute) creep test is run at Test Load.
- Proof Tests are simpler, requiring no cycling and are conducted to the same stress limits. The option is provided to return to Alignment Load prior to lock-off (in order to measure the permanent movement at Test Load), otherwise this movement can be estimated from measurements from representative Performance Tests.
- Supplementary Extended Creep Tests are not normally performed on rock anchors, except when installed in very decomposed or argillaceous rocks. A load cell is required and the load steps and reading frequencies are specified.
- Lock-off load shall not exceed 70% F_{pu}, and the wedges will be seated at 50% F_{pu} or more.
- The initial lift-off reading shall be accurate to 2%.
- There are three acceptance criteria for every anchor:
  - Creep: less than 1 mm in the period 1 to 10 minutes, or less than 2 mm in period 6 to 60 minutes.
  - Movement: there is no criterion on residual movement, but clear criteria are set on the minimum elastic movement (equivalent to at least 80% free length plus jack length) and the maximum elastic movement (equivalent to 100% free length, plus 50% bond length plus jack length).
  - Lift-Off Reading: within 5% of the designed Lock-Off load.
- A decision tree guides practitioners in the event of a failure in any one criterion. The "enhanced" creep criterion is 1 mm in the period 1 to 60 minutes at Test Load.
- The monitoring of service behavior is also addressed. Typically 3 to 10% of the anchors are monitored (if desired), by load cells or lift-off tests. Initial monitoring is at 1 to 3-month intervals, stretching to 2 years later.

- Epoxy-coated strand (Supplement)

This material and its use was first discussed systematically in 1996, although minor references had been made in 1986. The 2004 document contains a separate supplement dealing with specifications, materials, design, construction and testing, being a condensed and modified version of a 2003 document produced by the ADSC Epoxy-Coated Strand Task Force in November 2003. The Scope (Section 1) notes that anchors made from such strand "require experience and techniques beyond those for bare strand anchors." The supplement is a condensed version of the "Supplement for Epoxy-Coated Strand" as prepared by the ADSC Epoxy-Coated Strand Task Force (November 2003). It supplements the recommendations provided in the general recommendations with respect to specifications/ responsibilities/submittals; materials; design; construction; and stressing and testing.

3. BIBLIOGRAPHY

A comprehensive literature survey was completed to identify published dam anchoring case studies and various publications documenting the evolution of North American dam anchoring practices and construction methods. A total of 208 technical papers have so far been collected and compiled relating to North American post-tensioned rock anchoring projects. Hard copy and electronic versions of each have been collected. Figure 2 shows the number of publications by year indicating that over the first 5 years of the 21^{st} century the industry is publishing at a rate of about 13 papers per year. These papers relate to over 200 dams. Over 36% of the papers have been published in the proceedings of annual dam safety and society meetings.

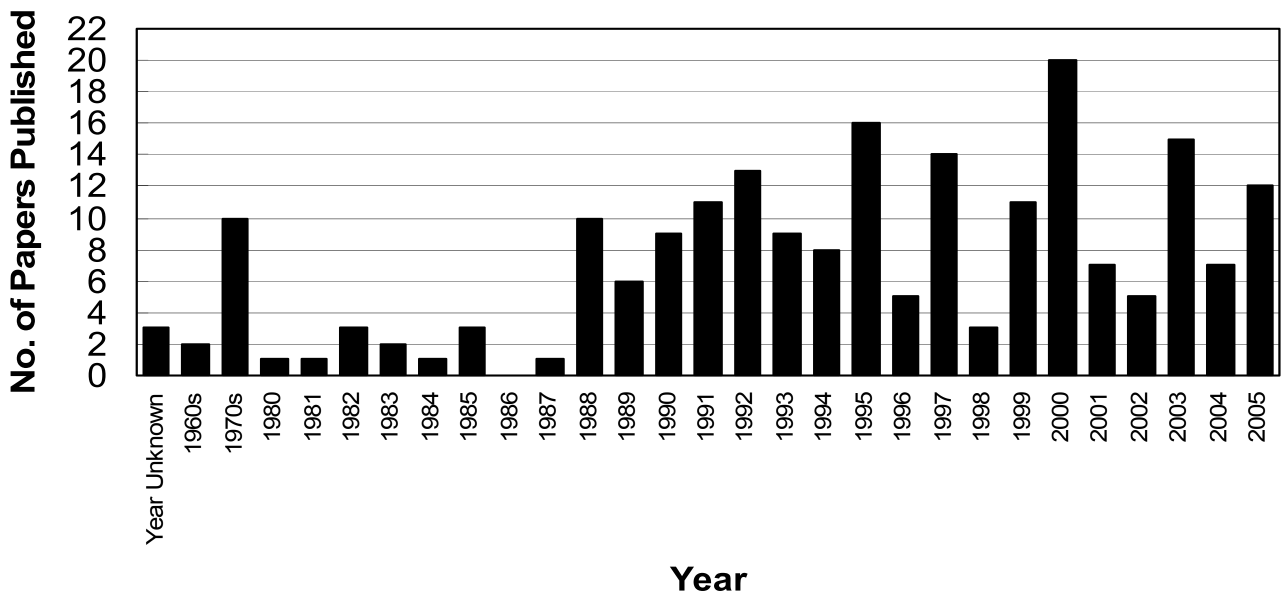


Figure 2. Histogram of dam anchoring publications by year.

4. ANALYSIS OF ANCHOR CASE STUDY DATA

The Rock Anchors for Dams National Research Project identified 393 dam anchoring project case studies. Figure 3 presents a histogram of North American dam post-tensioned anchoring projects identified during the Phase 1 data collection.

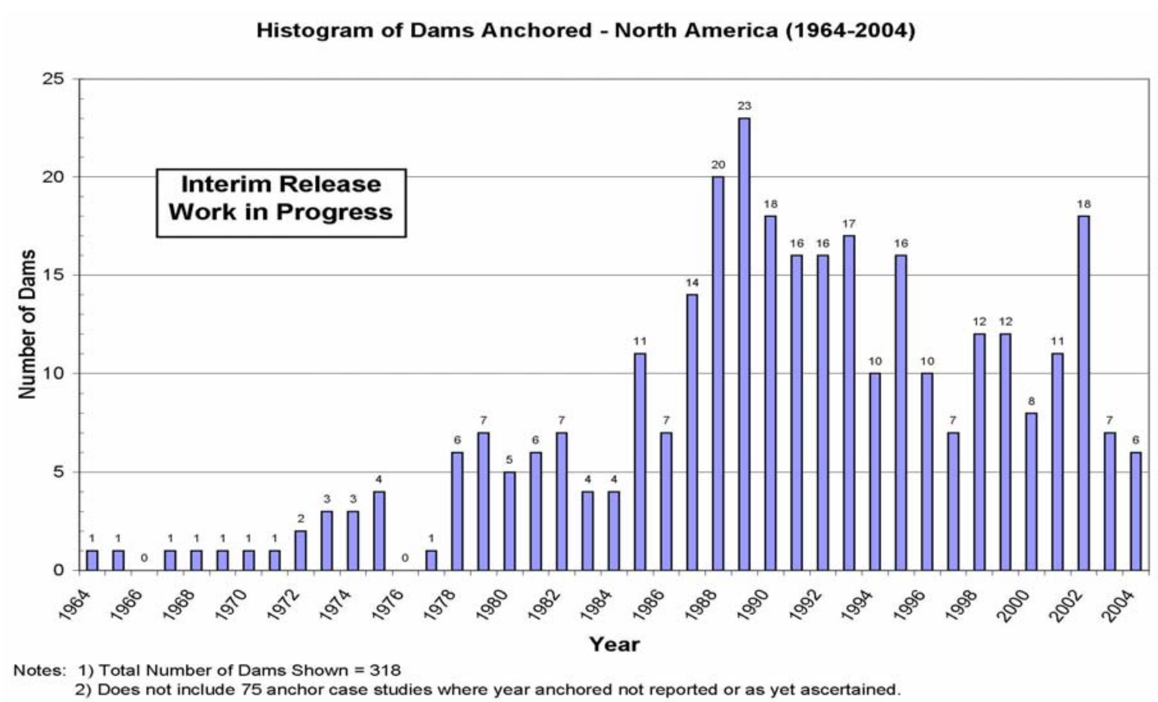


Figure 3. Histogram of Dams Anchored by Year

The graph reveals that over 318 anchoring projects were completed between 1964 and 2004, ranging from as few as one per year during the initial decade of North American anchoring practice to a maximum of 23 dam anchoring projects in 1989. More recently in 2002, 18 anchoring projects were constructed in a single year. Over the 40-year period, more than 20,000 tendon anchors were installed in North American dams, averaging over 500 anchors installed and tested per year.

The Phase 1 data collection focused on obtaining key information needed to characterize the post-tensioning market for dams over the past 40-years, including the following key data:

1. Dam Name
2. Location
3. Year Anchored
4. Number of Anchors
5. Type of Anchor Tendon (bar, stand, or wire)
6. Strand / Bar Size
7. Number of Strands per Tendon
8. Average Length

The case studies are grouped into the following three status categories for Phase 1:

1. Complete - all key data identified
2. Nearly Complete – missing one or two pieces of key data
3. Incomplete – little information available other than name of dam

Table 3 presents a list of the 239 anchor case studies classified as "Complete". Table 4 presents a list of the 50 case studies classified as "Nearly Complete". Table 5 presents a list of the 104 case studies classified as "Incomplete". The combined 154 nearly complete and incomplete case studies include the 75 case studies shown on Figure 3 for which the year of the anchoring project has yet to be ascertained.

Table 3. Complete Phase I Case Studies (239 Case Studies)

Anchor Case Studies			
Dam Name	**Location**	**Year Anchored**	**# Anchors**
CANADA			
Bearspaw River Intake/Pump St.	Calgary, AB	1987	38
Big Eddy Dam	Sudbury, ON	1999	29
Chaudiere No. 4 GS -Flume Wall	Ottawa, ON	2002	14
Chaudiere No. 4 GS - Intake/Channel Walls	Ottawa, ON	1999	35
Cheakamus Dam	Squamish, BC	1985	66
Comox Lake Dam	Courtenay, BC	1989	34
Dickson Dam	Innisfail, AB	1982	1200
Falls River Dam Rehab.	Prince Rupert, BC	1992	51
Ghost Dev. S. Overflow Spillw.	Cochrane, AB	1988	53
Ghost Development Main Dam	Cochrane, AB	1987	208
Ghost Development Power House	Cochrane, AB	1988	11
Ghost Development, Temp. Pier	Cochrane, AB	1986	16
Glenmor Dam Modification	Calgary, AB	1988	120
High Falls Generating Station	Wawa, ON	1999	8
Island Fall Dam	Creighton, SK	1987	45
John Hart Dam	Campbell, BC	1987	77

Anchor Case Studies			
Dam Name	**Location**	**Year Anchored**	**# Anchors**
Jordan R. Dam Rehab	Sooke, BC	1989	150
Kananaskis Dam Modifications	Canmore, AB	1988	10
Ladore Dam	Campbell, BC	1987	60
Laurie River Dam	Lynn Lake, MB	1993	45
Minden Generating Station	Lindsay, ON	2002	9
Mount Lake Dam	Elliot Lake, ON	2002	15
Nipawin Dam (Francois-Finlay)	Nipawin, SK	1983	996
Pine Falls GS - Gravity Wall Dam	Pine Falls, MB	2001	39
Pointe du Bois Dam - East Forebay Wall	Pointe du Bois, MB	2002	6
Pointe du Bois Dam Power House	Pointe du Bois, MB	2000	48
Rabbit Lake (control structure)	Temagami, ON	2003	2
Seven Mile Dam	Waneta, BC	2002	57
Stave Falls Dam	Mission, BC	1985	30
Upper Limestone Dam	MB	1987	2000
Whitehorse Unit #4	Whitehorse, YT	1982	9
Wilsey Dam	Vernon, BC	1992	14
USA			

Anchor Case Studies			
Dam Name	Location	Year Anchored	# Anchors
99 Islands Hydro Station	Gaffney, SC	2004	48
Allen's Falls Dam	Parishville, NY	1990	22
Bagnell Dam - Osage Hydroelectric	Miller County, MO	1981	287
Barker Dam	Nederlands, CO	1984	94
Bay Springs Lock and Dam	Tupelo, MS	1978	2
Black Rock Lock	Buffalo, NY	2002	55
Bluestone Lake Dam Test Program	Hinton, WV	2002	12
Boonton Dam	Jersey City, NJ	1992	112
Boundary Dam	Northport, WA	1993	13
Boyds Corner Dam	Putnam, NY	1988	33
Braddock Lock & Dam	Duquesne, PA	2003	63
Breckenridge Dam	Quantico, VA	1989	17
Buchanan Dam	Burnet, TX	2001	138
Buck Dam	Ivanhoe, VA	1993	82
Burt Dam	Buffalo, NY	1991	1
Burton Dam	Clayton, GA	1990	148
Cadyville Dam	Cadyville, NY	1997	35
Camino Penstock	CA	2000	61
Cannelton Dam	Cannelton, KY	1972	27
Cannelton Dam	Cannelton, KY	1997	148
Canton Dam	Canton, OK	2003	6
Capitola Dam	Madison County, NC	1984	35
Carpenter Dam	Little Rock, AR	1990	18
Cascade Dam	Berlin, NH	1986	23
Cave Mountain Lake Dam	Natural Bridge, VA	2000	15
Center Hill Dam	Lancaster, TN	1973	12
Center Hill Dam	Lancaster, TN	1994	10
Chalk Hill Dam	S.E. of Niagara, MI	1995	14
Chickamauga Lock & Dam	Chattanooga, TN	1995	273
Cliff Lake Dam	Sullivan County, NY	2002	3
Conowingo Dam	Port Deposit, MD	1978	537
Crescent Dam	Cohese, NY	1988	151
Curtis Dam	Corinth, NY	1989	40

Anchor Case Studies			
Dam Name	Location	Year Anchored	# Anchors
David D. Terry Lock and Dam	Little Rock, AR	2005	6
Delta Dam	Rome, NY	1983	93
Devils Gate Dam	Pasadena, CA	1996	17
Difficult Run Dam		1979	26
Douthat Dam Spillway	Clifton Forge, VA	1997	9
Dundee	Portland, ME	1989	13
East Sidney Dam	Near Franklin, NY	1989	92
Eastman Falls Dam	Lincoln, NH	1998	17
Eastvale Dam	Beaver Falls, PA	1993	22
Echo Lake Dam	Union County, NJ	2001	21
Edgar M. Hoopes Dam	Wilmington, DE	1979	10
Edgar M. Hoopes Dam	Wooddale Area, DE	1982	12
Elkhart Dam	Elkhart, IN	1986	31
Elwha Dam	Lower Elwha Indian Res., WA	1986	9
Farrington Dam	New Brunswick, NJ	1990	10
Five Falls Dam	South Colton, NY	1990	20
Fontana Dam	Robbinsville, NC	1997	127
Franklin Falls Dam	Franklin, NH	1980	39
Fulton Lock & Dam	Fulton, NY	1992	21
Glens Falls Dam	South Glens Falls, NY	1993	7
Glens Falls Feeder Dam	South Glens Falls, NY	1997	26
Glines Canyon Dam	Lower Elwha Indian Res., WA	1989	11
Goat Rock Dam	Columbus, GA	2001	14
Goat Rock Dam	Columbus, GA	1985	139
Grays Landing Lock & Dam	Grays Landing, PA	1994	37
Great Falls Dam	Rock Island, TN	1989	114
Green Swamp Dam #2	Wanaque, NJ	1985	61
Green Swamp Dam #4	Wanaque, NJ	1985	15

Anchor Case Studies			
Dam Name	Location	Year Anchored	# Anchors
Greenup Locks & Dam	Wheelersburg, KY	1980	20
Greggs Falls Dam	Merrimack River, NH	1991	21
Guist Creek Lake Dam	Rivals, KY	1995	21
Habersham Mills Dam	Habersham, GA	1981	106
Hauser Dam	Helena, MT	1998	20
High Dam	Oswego, NY	1993	56
High Falls Dam	Colton, NY	1990	24
High Rock Dam	Charlotte, NC	1999	19
Highgate Falls	Village of Swanton, VT	1992	22
Hildebrand Dam	Morgantown , WV	1974	70
Hiwassee Dam	Murphy, NC	1992	140
Hodenpyl Dam (Phase II)	Mesick, MI	2002	4
Holter Dam	Craig, MT	1988	22
Huntsville Dam	Huntsville/Dallas, PA	1988	14
Hydroelectric Project (Benton Falls)	Benton Falls, ME	1995	21
Ingham Hydro	Little Falls, NY	1995	14
J.T. Myers Lock & Dam (Phase II)	Mt. Vernon, IN	2002	12
Jed Johnson Dam	Cache, OK	2001	43
John Hollis Bankhead Lock and Dam (I)	Howse Camp, AL	1965	16
John Hollis Bankhead Lock and Dam (II)	Howse Camp, AL	1969	160
Johnsonville Dam	Pittston, NY	1988	32
Junction Falls	River Falls, WI	1989	15
Kent Falls Dam	Plattsburgh, NY	1991	17
Kent Falls Dam	Morrisonville, NY	1995	4
Kerr Dam	Agency, MT	1995	3
Lake Flower Dam	Saranac Lake, NY	1986	6
Lake Ilo Dam	Dunn Center, ND	1996	100
Lake Lenape Dam	Mays Landing, NJ	1991	23

Anchor Case Studies			
Dam Name	Location	Year Anchored	# Anchors
Lake Lynn Dam	Point Marion, WV	1974	16
Lake Lynn Dam	Point Marion, WV	1990	75
Lake Milton Dam (Phase II)	Columbus, OH	1988	32
Lake Milton Dam (Phase I)	Columbus, OH	1975	59
Lake Raleigh Dam	Raleigh, NC	1983	7
Leesville Dam	Leesville, VA	2001	47
Libby Dam	Libby, MT	1971	90
Liberty Dam	Daniels City, MD	1979	10
Lighthouse Hill Dam	Altmar, NY	1994	122
Little Falls Dam	Spokane, WA	1998	16
Little Goose Lock and Dam	Pasco, WA	1968	28
Lock and Dam I	Minneapolis, MN	2000	135
Lock and Dam I	Minneapolis, MN	1979	114
Lock C-3 Dam	Mechanicsville , NY	1990	11
Locks & Dam No. 26	Alton, IL	1978	9
London Locks & Dam	London, WV	2002	27
Long Lake Dam	Spokane, WA	1989	5
Lower Great Falls Dam	Rollinsford, NH	1985	20
Lower Salmon Power Plant	Twin Falls, ID	1992	30
Madison Dam	Ennis, MT	1989	62
Marmet Lock & Dam	Kanawha County, WV	2005	537
Martin Dam	Tallassee, AL	1992	63
Martin Dam, Unit 3	Tallassee, AL	1979	8
Martin Dam, Units 1, 2 & 4	Tallassee, AL	1983	24
Mathis Dam	Lakemont, GA	1991	67
Max Starcke Dam	Marble Falls, TX	2001	40
McAlpine Dam	Louisville, KY	2002	77
McDaniel Lake Dam/Spillway Modification	Springfield, MO	1988	221
Melzingah Dam	Dutchess Junction, NY	1993	9

Anchor Case Studies			
Dam Name	**Location**	**Year Anchored**	**# Anchors**
Merwin Dam	Woodland, WA	1990	16
Michigamme Falls	Michigamme, MI	1992	4
Mill Street Dam	Auburn, NY	1999	21
Millers Ferry Lock, Dam and PH	Midway, AL	1990	9
Milltown Dam	Missoula, MT	1989	12
Minidoka Dam	Heyburn, ID	1996	7
Mitchell Dam	Wetumpka, AL	1981	18
Monongahela River No. 2 Locks	Braddock, PA	2000	156
Montgomery Lock and Dam	Beaver, PA	1985	379
Morgan Falls Dam	Dunwoody, GA	1985	97
Mount Beacon Reservoir Dam	Beacon, NY	1993	15
Nacoochee Dam	Tallulah Falls, GA	1987	20
Newburgh Dam	Newburgh, IN	1973	18
Newport Dam No. 1	New Port, VT	1991	37
Newton Falls Upper Dam	Newton Falls, NY	1989	11
Norfolk Falls Dam	Norfolk, NY	1991	92
Occoquan Dam	Occoquan, VA	1992	54
Ocoee No. 1 Dam	Parksville, Polk County, TN	1975	48
Ogdensburg Dam	Ogdensburg, NY	1991	29
Olmos Dam	San Antonio, TX	1995	3
Oneida City Reservoir Dam	Oneida, NY	1988	13
Oswego Falls	Fulton, NY	1992	32
Oxford Dam	Hickory, NC	2002	75
Pacoima Dam	Pacoima, CA	1999	8
Pacoima Dam	Pacoima, CA	1975	35
Palmer Falls Hydro	Cornith, NY	1986	64
Pardee Dam	Jackson, CA	1995	48
Peavy falls	Iron Mountain, MI	1990	3
Pickwick Landing, Auxiliary Lock	Savannah, TN	1978	68
Pickwick Landing, Auxiliary Lock Chamber	Savannah, TN	1981	61

Anchor Case Studies			
Dam Name	**Location**	**Year Anchored**	**# Anchors**
Piercefield Dam	Stark, NY	1990	10
Pineview Dam	Hermitage, UT	2002	48
Piney Creek Dam	Piney, PA	1982	6
Pit No.7 Dam	Redding, CA	1973	6
Point Marion Lock and Dam	Point Marion, PA	1991	471
Point Marion Lock and Dam	Point Marion, PA	1988	63
Post Falls Middle Channel	Greenacres Subdivision, ID	1995	5
Post Falls South Channel	Greenacres Subdivision, ID	1995	6
Prospect Hydro Dam	Trenton Falls, NY	1993	3
Railroad Canyon Dam	Lake Elsinore, CA	1996	15
Rainbow Falls Dam	Pottsdam, NY	1989	38
Reeds Pond Dam	Susquehanna County, PA	1994	4
Remmel Dam	Hot Springs, AR	1998	22
Rhodhiss Hydro Station	Hickory, NC	2001	39
Richard B. Russell Dam	Augusta, GA	1981	31
Ridgway Dam	Colona, CO	1985	51
Rio Dam	Sullivan, NY	1996	22
Robert Byrd Lock & Dam (Gallipolis)	Hogsett, WV	1997	124
Robert Byrd Lock & Dam (Gallipolis)	Hogsett, WV	1994	124
Rogers Dam	Big Rapids, MI	1994	12
Roy Inks Dam	Burnet County, TX	2001	46
Rush Creek Meadows Dam	June Lake, CA	2004	10
Ryan Dam	Fort Benton, MT	1970	31
Safe Harbor Dam	Conestoga, PA	1999	52
Saluda Dam	Irmo, SC	1995	20
Sandstone Rapids Dam	Crivitz, WI	1989	17
Santeetlah Dam (Phase II)	Robbinsville, NC	1998	8
Santeetlah Dam (Phase III)	Robbinsville, NC	2001	13

Anchor Case Studies			
Dam Name	Location	Year Anchored	# Anchors
Schaghticoke Dam	Troy, NY	1991	3
Schuylerville Dam	Schuylerville, NY	1990	26
Shepaug Dam	Berkshire Estates, CT	1988	97
Sherman Island Hydro Project Dam	Queensbury, NY	1991	2
Shockoe Dam	Richmond City, AL	1980	729
Soda Dam	Soda Springs, Idaho	1990	31
South Fork Tolt Dam	Seattle, WA	1998	6
St. Anthony Falls Lower Lock & Dam	Minnesota, MN	1982	5
Stevens Creek Dam	Martinez, GA	2002	40
Stevenson Dam	Danbury, CT	1987	80
Stewart Mountain Dam	Mesa, AZ	1991	84
Sugar Hollow Dam	Whitehall, VA	1998	23
Sylvan Lake Dam	Rome City, IN	1995	283
Tarryall Dam	Deckers, CO	2003	8
Titicus Dam	Purdy Station, NY	1998	9
Tom Miller Dam	Austin, TX	2004	55
Townsend Lake Dam	Ossipee, NC	1980	18

Anchor Case Studies			
Dam Name	Location	Year Anchored	# Anchors
Tugalo Dam	Tallulah Falls, GA	1989	70
Upper Occoquan Dam	Occoquan, VA	1992	56
Wallenpaupack Dam	Hawley, PA	1986	33
Wallenpaupack Dam	Hawley, PA	1979	12
Walnut Creek - Wells Branch Dam	Austin, TX	2005	35
Webber Dam	Lansing, MI	1995	20
Wesley Seale Dam	Corpus Christi, TX	1998	4
Whitney Point Dam	Whitney Point, NY	1989	18
Wilde Lake Dam	Columbia, MD	1994	42
Wilson Dam	Muscle Shoals, AL	1982	8
Wirtz Dam	5 miles west of Marble Falls, TX	1999	78
Worumbo Dam	Lisbon Falls, ME	1988	37
Wylie Dam	Fort Mill, SC	2004	72
Yonah Dam	Tallulah Falls, GA	1988	53

Table 4. Nearly Complete Phase 1 Case Studies (50 Case Studies)

Anchor Case Studies			
Dam Name	**Location**	**Year Anchored**	**# Anchors**
CANADA			
Calm Lake Dam	Fort Frances, ON		18
Carmichael Falls Hollow Dam	Kapuskasing, ON	1995	2
Corra Linn Dam	Nelson, BC	1992	107
Corra Linn Dam	Nelson, BC	1991	11
Gartshore & Hollingworth Dam	Wawa, ON		15
Keenleyside Dam	Castlegar, BC	1999	14
Lac Seul Dam	Ear Falls, ON		144
Lower Bonnington Dam	Nelson, BC	1993	26
Mamquam River Dam	Squamish, BC		25
McVittie Generating Station	Sudbury, ON		8
Rapides des Quinze Dam	Angliers, QC		18
Seymour Falls Dam	Vancouver, BC		30
St. Raphael Dam	Quebec		18
Stinson Dam	Sudbury, ON		10
Upper Bonnington Dam	Nelson, BC	1993	16
Wahnapitae Dam	Ontario		76
USA			
Allegheny Ltd. Hydro	PA		15
Barkley Lock & Dam	Gilbertsville, KY	1998	26
Bath County Pumped Storage	Warm Springs, VA	1982	24
Black Eagle Dam	Great Falls, MT	1993	
Bloodsgood Pond Dam	Union, NJ	1998	
Byllesby Dam	Ivanhoe, VA	1992	82
Canyon Dam	Eager, AZ		15
Combie Dam	Meadow Vista, CA		16
Condit Dam	Underwood, WA	1972	25

Anchor Case Studies			
Dam Name	**Location**	**Year Anchored**	**# Anchors**
Cowans Ford Hydro Station	Stanley, NC	2000	73
Cross River Dam	Katonah, NY	1997	30
Dam 19	Essex, VT	'90?	23
Dashields Lock & Dam	Pittsburgh, PA		74
Dead River Dam	Marquette, MI	1994	40
East Norfolk Hydro Dam	Norfolk, NY	1991	78
East Norfolk Hydro Dam (Phase II)	Norfolk, NY	1993	3
East Side Reservoir Intake Tower	near Hemmet, CA		28
Fontana Dam	Robbinsville, NC	1974	25
Forks of Butte Hydro	Chico, CA	1990	153
Ft. Fitchey		1979	
Houston Power & Light Dam	Baytown, TX		17
Little Quinesec Hydroelectric Dam	Niagara, WI	1998	11
Lloyd Shoals Dam	Lloyd, GA	1990	53
Loch Raven Dam	Baltimore, MD	2004	
Lookout Shoals Hydro Station	Statesville, NC	2000	24
Mianus River Dam	Greenwich, CT		13
Red Bridge Hydro	Wilbraham, MA	1993	9
Rocky Creek Dam	Great Falls, SC	2002	30
South Edwards Dam	Oswegatchie, NY		8
South Glens Falls Power Station	South Glens Falls, NY	1993	101
Spiers Falls Dam	Corinth, NY	1989	
Wilder Dam (NEPCO)	Wilder, VT		28
Williams Bridge Reservoir	Scranton, PA	1985	47
Yates Dam	Tallahassee, AL	1996	46

Table 5. Incomplete Phase I Case Studies (104 Case Studies)

Anchor Case Studies			
Dam Name	**Location**	**Year Anchored**	**# Anchors**
CANADA			
Aber Feldie Dam	Fernie, BC	1999	
Auburn Generating Station	Peterborough, ON	2003	
Bishop's Falls G.S.	Grand Falls-Windsor, NF		
Buntzen Dam	Ioca, BC		
Cedar Lake (Noreng)	Temagami, ON	2002	
Comox Lake Dam	Courtenay, BC	2000	
Crystal Falls Generating Station	near North Bay, ON	1987	
Ruskin Dam	Mission, BC	2007	
Seven Mile Lake Dam	West Muskosh, NB	1964	
Stave Falls Dam (Blind Slough Dam)	Mission, BC	2006	
Sugar Lake Dam	Vernon, BC	1985	12
Sugar Lake Dam	Vernon, BC	2002	
Thornbury Dam	Thornbury, ON	2001	
USA			
Allegheny Locks 5 & 6	Emsworth, PA		
Alum Creek Lake Dam	Westerville, OH		
Avista HED	WA		
Banister Dam	Halifax, VA	1996	
Belleville Power House	Longbottom, WV		
Blunn Dam	Arvada, CO		
Boney Falls (Escanaba No. 4)	Wells, MI		
Bonneville Lock and Dam	Portland, OR		
Brandon Rd. Lock Rehab Stage 1	Joliet, IL	1984	
Briar Hydro	Penacook, NH	1987	
Browns Falls Dam	Pittstown, NY		
Cedar Falls Hydro	Menomonie, WI	1999	176
Champlain Canal Lock	Saratoga County, NY	1992	
Chickamauga Lock & Dam	Chattanooga, TN	1984	
Clark Falls Dam	Milton, VT	1993	32
Colebrook Dam	Riverton, CT		

Anchor Case Studies			
Dam Name	**Location**	**Year Anchored**	**# Anchors**
Combined Locks Dam Hydro Project #2715	Combined Locks, WI	1991	
Deerfield #5 Dam	MA		
Delaware Dam Repair	Delaware, OH		
Derby Shelton Hydro	Derby/Shelton, CT		
Dolby Dam	Millinocket, ME	1995	7
Elmer Dam	Belfort, NY	1989	8
Emporia Dam	Emporia, VA	1994	19
Flat Rock Dam	Fine, NY		31
Flint River	Albany, GA	1994	
Fond Du Lac	Duluth, MN		
Fontana Dam	Robbinsville, NC	1989	
Fontenelle Dam	La Barge, WY		
Four Mile Wall	Alpena, MI	1989	
French Canyon Dam	Tieton, WA		
Friant Dam	Fresno, CA		
Gem Lake Dam	June Lake, CA		
Gladfelter Mill Dam	Carlisle, PA		
Gregory Jarvis Hydro (Hinckley Dam)	Hinckley, NY		
Hardy, Croton & Hodenpyl Dam	MI		
Headgate Dam	Parker, AZ		
Hells Gate Dam	Pasadena, CA		
Hillhouse Lake Dam	Lawley, AL		
Hillview Reservoir	Yonkers, NY		30
Hinckley Dam	Hinckley, NY	1987	
Hodenpyl Dam (Phase I)	Mesick, MI	1996	
Hollister Dam	Scranton, PA	1987	
Hollywood Reservoir (Mulholland)	Los Angeles, CA		
Hoover Dam	Boulder City, NV		
Howard Hansen Dam	Auburn, WA		
Iron Bridge Dam	Point, TX	1990	

Anchor Case Studies			
Dam Name	**Location**	**Year Anchored**	**# Anchors**
John Day Lock & Dam	Rufus, OR	2004	
John Day Lock & Dam	Rufus, OR	1981	
Kenchhoff Dam	Oakhurst, CA		
Kentucky Reservoir Dams	Calvert City, KY		
La Prele Dam	Douglas, WY	1978	
Lake Milton Dam (Phase II)	Youngstown, OH	1988	
Lake Tanglewood Dam	12 miles SE of Amarillo, TX	1996	
Littleville Dam	Huntington, MA		
Lock and Dam 3	Elizabeth, PA	1977	
Lower Watertown Dam	Watertown, WI	1992	
Lyons Falls Hydro	Lyons Falls, NY		
Manalapan Dam	Jamesburg, NJ	1988	
Middle Falls Hydro	Middle Falls, NY		
Mill.... (sp?) Station Power House	Lansing, NY		
Milton Lake Dam	Youngstown, OH	1975	
Missisquoi Hydro	VT		
Moosehead Dam	Moosehead Lake, ME	1990	
Morrow Point Dam	Austin, CO	1967	25
Nine Mile Dam	Spokane, WA		
Olmos Dam	San Antonio, TX	1978	
Pelzer Dam (Upper)	Pelzer, SC	1996	12
Pine Grove Dam	PA		
Pueblo Dam	Peublo, CO		
Pumpkin Hill Hydro/Lowell Tannery	East Lowell, ME		
Putnam Reservoir Dam	Greenwich, CT	1999	
Ravine Lake Dam	Far Hills, NJ		400
Rising Dam	Agawam, MA	1991	23
Rocky Reach Dam	Wenatchee, WA		
S. Colton & Five Falls Dams	S. Colton, NY		

Anchor Case Studies			
Dam Name	**Location**	**Year Anchored**	**# Anchors**
Santeetlah Dam (Phase I)	Cocran Creek Road Village, NC	1980	
Scranton Dam	Scranton, PA	1988	
Seneca Falls Powerhouse	Seneca Falls, NY		
Shaver Lake Dam	Shaver Lake, CA	2003	
Shelburne Powerhouse Long Falls Dam	PA		
Sheldon Springs Hydro	St. Albans, VT	1989	
Soda Spring Dam	Idelyld Park, OR		
Sodom and Bog Brook Dams	Brewster, NY	2003	
Starved Rock Hydro Project - Contract 3	Utica, IL	1993	
Steel Dam	Milan, IL	1987	
Taft Youth Center Dam	Herbert Domain, TN		
Upper Falls Hydro Penacook	Penacook, NH	1987	
Upper Fulton Dam	Fulton, NY	1988	22
Wanapum Dam	Richland, WA		
Waterford Dam	Pleasantdale, NY	1989	
Weston Mill Pond Dam	New Brunswick, NJ		

In order to wrap-up the Phase 1 research, it is crucial to track down the remaining key information for the case studies classified as “Nearly Complete” (Table 4) and obtain additional information where possible for those case studies listed as “Incomplete” (Table 5). The authors respectfully request assistance reviewing these case study lists and provide any information that could help complete the missing information.

5. CONCLUSIONS

The first phase of the Nation Research Project on Rock Anchors for Dams involved three major tasks: 1) Study the evolution of North American anchoring practice through industry “recommendation” documents, 2) collect and review published case histories and other publications documenting North American anchoring practices, and 3) develop of a comprehensive list of North American dam anchoring projects and an interactive database of case study information.

The significant Phase 1 findings include:

- North American practice has evolved substantially over the past forty years through emphasis on technology and refinements in construction techniques. Particular progress has been made in the areas of corrosion protection, quality control, and testing procedures.
- Prestressed rock anchors have been used successfully in North America on nearly four hundred dams and well over 20,000 installed anchor tendons.
- The successful use and application of prestressed anchors for dams is well documented by more than 200 published case studies, journal articles, and technical reference documents.

Phase 2 of the National Research Project on Rock Anchors for Dams will focus on the engineering and performance aspects of prestressed rock anchors in dams. The repository of published articles and technical literature will be used to further trace the evolution of anchoring practices, including the purpose and engineering justification for anchor systems, considerations for particular geologic conditions, site investigation and test anchor programs, and long term performance results.

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References

ADSC Epoxy-Coated Strand Task Force. (2003). “Supplement for Epoxy-Coated Strand,” ADSC: The International Association of Foundation Drilling, November.

Bruce, D.A. and J.S. Wolfhope. (2005). “Rock Anchors for Dams: The Preliminary Results of the National Research Project,” ASDSO Dam Safety Conference, Orlando, FL, September 23-26, 6 pp.

Bruce, D.A. and J.S. Wolfhope. (2006). “Rock Anchors for Dams: The National Research Project: The Evolution of Post-tensioned Anchors on Hydropower Dams,” Hydrovision 2006, Portland, OR, July 31-August 4, 11 p.

National Rock Anchor Research Program. (2005). “High Capacity Rock Anchors for Dams: Thirty Years of Recommendations for Practice,” Geo^3 GEO Construction Quality Assurance/Quality Control Conference Proceedings, Editors D.A. Bruce and A.W. Cadden, Dallas/Ft. Worth, TX, November 6-9, pp. 88-105.

Prestressed Concrete Institute (PCI). (1974). “Tentative Recommendations for prestressed rock and soil anchors.” First Printing, Phoenix, Arizona. 32 p.

Post Tensioning Institute (PTI). (1980). “Recommendations for prestressed rock and soil anchors.” First Edition, First Printing, Phoenix, Arizona. 57 p.

Post Tensioning Institute (PTI). (1986). “Recommendations for prestressed rock and soil anchors.” Second Edition, First Printing, Phoenix, Arizona. 41 p.

Post Tensioning Institute (PTI). (1996). “Recommendations for prestressed rock and soil anchors.” Third Edition, First Printing, Phoenix, Arizona. 70 p.

Post Tensioning Institute (PTI). (2004). “Recommendations for prestressed rock and soil anchors.” Fourth Edition, First Printing, Phoenix, Arizona. 98 p.