# Progress and Developments in Dam Rehabilitation by Grouting

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## Abstract

Grouting techniques are an integral part of new dam construction. They have also had considerable value as a remedial tool. In recent years however, there have been highly significant advances in materials, methods and techniques which have increased remarkably the scope and power of grouting in remedial applications. The paper summarizes the key areas of progress with reference to case histories involving various grouting applications for seepage and settlement control, and seismic mitigation.

## Introduction

Several recent publications (1-5) highlight the problems posed by the passage of time to the safety and efficiency of our hydraulic structures. They equally underline the momentum within the dam engineering community towards analysis, monitoring and rehabilitation. This situation has stimulated the efforts of all interested parties, but especially those of the specialist geotechnical contractor. Seduced by the prospect - not totally without logic or reality - of "cornering" a particular aspect of the dam rehabilitation market at a time of decline in new dam projects, this group has generated a growing number of novel and occasionally exotic options for problems involving seepage, movement and seismicity. New techniques of drilling and injection are being paired with new generations of grouting materials to provide effective, engineered solutions. Equally as important is the current contractual climate. It is a sad but accurate observation that the stifling procurement and contracting practices of the last four decades in this continent have led to an ossification of practice and a studied ignorance of innovation elsewhere. The efficiency and reputation of grouting has therefore rarely reached foreign heights. However, in the last few years, there has been growing and encouraging evidence of a fundamental change in approach (6). Major Federal agencies are awarding large dam remediation contracts largely on the basis of the excellence of

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comprehensive technical proposals assuming they are in a financially reasonable range. Major utilities are following suit. This trend plays to the strengths and advantages of all concerned, and not least of all it gives the contractor the stimulus to innovate and to advance his technology. While grouting, like any other technique, cannot be regarded as a general panacea, examination of case histories proves it can be a reliable, respectable engineering tool if properly designed, conscientiously conducted and equitably rewarded. Bad experiences can usually be traced to inappropriate applications, poor execution by contractors, or major financial disputes all three factors display a mutual magnetism at project's end. Not infrequently, all three factors display a mutual magnetism.

This brief review provides a generic guide to the various categories of remedial applications in which grouting has been successfully used for dams. Reference is made to the specific case histories, although space limitations prevent detailed descriptions: the interested reader is encouraged to locate the original publications. Mostly these projects have involved North American expertise in their engineering and execution: certain overseas examples are also included to illustrate key advances not yet reported in the USA or Canada. Between them, these case histories describe grouting for concrete and embankment structures; in soil and rock; and for seepage control, underpinning and liquefaction mitigation. The list is not comprehensive, of course: many excellent remedial grouting projects have not been widely publicized, while there is insufficient space to acknowledge the wide array of proprietary methods and materials growing in the concrete repair market, for example. The data cited can be supplemented by more recent publications and textbooks (7-14), and the proceedings of specialty conferences (15-17).

## Seepage Control

The loss of water through or under a dam is rarely just a question of volume, although in especially arid or marginal areas, losses may be significantly large to compromise storage, or generating capacity. More usually, seepage is a threat in terms of the foundation uplift pressures it may cause, or the internal erosion of embankment or foundation material which it transports. For example, foundation scour resulting from piping was blamed (18) for the 1989 failure of the St. Anthony Falls lower dam powerhouse on the Mississippi River, Minneapolis. The bedrock was a very friable and erodible Silurian sandstone: the structure had survived for 90 years before suddenly failing.

For embankment dams, seepage through the dam, at its contact, or in the immediate bedrock can be equally dangerous, especially in cases where insufficient internal filters were originally placed. Davidson (19) notes that "many of the most damaging dam failures in the United States have been caused by seepage induced piping", and named Teton Dam and Quail Creek Dam as prime examples. Most geologically based hazards involve bedrocks featuring: erodible seams or karsts; soluble minerals (e.g. gypsum); expansive minerals (e.g. anhydrite); and fissured/stratified ignimbrites.

However, it would seem that in many of the cases where remediation has been required, the cause has been the manner in which the initial grouting was conducted. Inappropriate selections with respect to drilling and grouting parameters and procedures lead to curtains which are inefficient at inception and progressively less effective with time. For example, Petrovsky (20) discussed the leaching of cementitious compounds from grout curtains as a function of the water-cement ratios, while Houlsby (21) also addressed the problem. This question of grout permanence is even more acute in the case of curtains in alluvials, formed with the earlier silicate based chemicals alone. Fortunately, this is not one of the problems facing the U.S. community, as such technologies were not routinely applied in the U.S. dams, during construction.

Another key factor in trying to account for the need for remedial grouting was touched upon by Benzekri and Marchand (22): "There is no precise and accurate way of checking how effective the drainage and grouting will be prior to filling the reservoir. Water tests in boreholes are useful in guiding the work as it proceeds and give an overall indication of how much permeability has been reduced; however, the results must not necessarily be taken at their face value. The only conclusive test is to fill the reservoir and observe seepage pressures and flow rates during, and for some time after, this period."

As a final introductory point, Davidson (19) reviewed five case histories of remedial grouting under embankment dams. He drew the following conclusions which should be borne in mind as the details of this paper's projects are considered:

- grouting may be successful in reducing seepage volumes but may still not significantly reduce piezometric levels, especially in soils or rocks with open but ungroutable pores or fissures.
- grouting may be only a temporary solution if the real cause is solution of a soluble horizon.
- attacking the seepage problem upstream with a clay blanket may be more cost effective.
- although state of practice methods and materials may have been originally used, they may now be judged as ineffective and inappropriate, in the light of current knowledge.
- the extent of knowledge of the foundation and embankment materials, and the construction history will greatly influence the accuracy of the analysis of the seepage problem.

## *Concrete/Masonry Dams*

### a. Grouting of the Structure

Grouting has been conducted where

- the amount of water loss per se has been significant in terms of storage loss;

- flow of water has caused structural deterioration by dissolution of bonding mortar or exploitation of lift joints;
- presence of water is causing potentially dangerous uplift pressures in the structure;
- presence of water is causing deep and persistent spalling on downstream faces (especially on north facing dams in mountainous areas) as a result of freeze-thaw;
- presence of water is fuelling the destructive alkali-aggregate reaction phenomenon (23);
- the dam is to be raised and its integrity must be guaranteed against the subsequent elevated hydrostatic forces;
- other remedial actions, e.g., prestressed rock anchors (24) are to be undertaken, requiring previous "enabling works".

The drilling technologies involved in such works are typically straightforward: the structure is materially competent and so permits "open holing" by rotary or rotary percussive rigs. Grouting is then performed through packers placed either at the collar or at predetermined depths dictated by the flow patterns. Both single and double packers are used depending on the technique, while stage grouting and split spacing techniques are commonly used, analogous to classic rock grouting practice (e.g. 25, 26).

However, it is in materials technology that most progress appears to have been made, and the following categories of grouts may be recognized: 1. cement based - conventional; 2. cement based - quick set; 3. chemical grouts - sealing; 4. epoxy resins - sealing and structural bonding. This simplistic categorization has its roots in the history and complexity of application as opposed to the complexities of materials science (27).

1. Cement Based - Conventional: Economic, particulate cement grouts, locally incorporating bentonite, flyash or sand, have long been the choice for simple leak sealing attempts. However, such grouts, with their relatively long setting times, are generally not effective in flowing water conditions, or for penetrating into fine fissures. In addition, their tendency to bleed at higher water-cement ratios compromises their efficiency in filling larger voids, while their brittleness when set is not compatible with good, long term performance in structures which strain seasonally. One very good example, however, was the 1961 sealing of the heart of the old Aswan Dam, Egypt (14), threatened when the soft Nile river water had dissolved the interblock mortar. Over 66,000 m of grout holes were installed to form an internal grout curtain split spaced in three phases, and featuring 3m ascending stages. The effectiveness of the work was later demonstrated visually by the complete drying up of the downstream face, while piezometer data confirmed that internal water levels had been substantially reduced.

2. Cement Based - Quick Set: To overcome the problem of long setting times, contractors have for long added sodium silicate solution or other compounds such as calcium chloride to cementitious grouts to induce "flash sets" in situ. This was applied to seal boreholes encountering flowing or artesian water, and has been adopted

with success in structural repair where limiting fissure widths or likelihood of subsequent structural movements can be discounted. The most recent example is the widely publicized sealing of Morris Sheppard Dam, Texas (28, 29). This flat slab buttress structure, the highest in the U.S., had been severely damaged by differential downstream movements leading to fissuring in the upstream foundation transition beam. These fissures permitted very high flows, and subbase piezometric heads equal to 65% of the lake head. Following a significant reduction in lake level, accelerated grouts were used to seal the fissured beam. Flows were reduced from 550 gpm to less than 1 gpm after secondaries, while the reservoir is now back to full capacity.

3. Chemical Grouts - Sealing: Textbooks (13) and comprehensive papers (27) have been devoted to the vast and complex arrays of chemical grouts. For reasons of permanence, toxicity, strength and cost, many of the families used elsewhere in geotechnical grouting are not generally viable. In this category falls sodium silicates, and some acrylamides and acrylates. Groups with actual or potential usefulness include silacsols (30), some acrylamides and acrylates, water reactive one component poly- urethanes (forming either hydrophobic or hydrophyllic gels, which can be rigid or flexible), and two component polyurethane elastomers (hydrophobic or hydrophyllic). A recent example of the use of a two-component polyurethane grout was at Easton Dam, CT (31). The downstream face of this 1926 dam exhibited large areas of surface spalling, joint spalling and efflorescence, with seasonal seepage through 16 vertical joints. Freeze thaw effects extended for at least 150mm, being especially severe in the uppermost 8m. The foam grout was placed in 150mm holes drilled vertically down through each joint, and reportedly had "attractive" adhesion, stretchability and non-shrink properties. Joint seepage was reduced by 80%. Most recently, polyurethanes have also been used with great effectiveness to seal lift joints and the concrete/rock contract zone, at a gravity structure, Soda Dam, ID, (32) and in the rather compacted concrete of Upper Stillwater Dam, OR (33). Active promotion and development by specialist contractors, and grout formulators, is ensuring a growing market for this approach.

4. Epoxy Resins - Sealing and Structural Bonding: There are occasions when the arresting of seepage alone is insufficient: concrete structures may have suffered some fundamental fracturing necessitating an equally fundamental structural rebonding. This is especially true with the new generation of high, thin, double curvature concrete dams in which foundation, design, construction or service phenomena may individually or collectively cause the problem. Equally numerous are cases in older gravity or arch dams where lake waters have exploited concrete lift joints, vulnerable from the onset as "soft" laitance rich planes, a legacy of high contemporary water contents in the concrete. Under such conditions and demands, the concept of using synthetic epoxy resins has been progressively exploited in the last decade (34, 35).

The diagnosis of the problem, and the planning of the repair are clearly vital. Likewise, the specialist drilling and injection techniques, devoted to step by step demonstration of effect and effectiveness, are honed to a high degree. However, the key to the success and vast potential of the technique - now referred to as RODUR - is the advances made in the material itself. Epoxy resins can now be formulated in a variety of ways to meet specific goals and applications (35) for the structural rebonding of high dams, often at full reservoir level and in fully operational conditions.

Excellent experience in major high dams throughout the world has been recorded. In the USA, Santeetlah Dam, NC, was repaired recently. This was an example of an older gravity structure, whose safety was increasingly compromised by massive seepage and high uplift pressures, through horizontal lift joints. In one 13m long block of the dam, flows of over 2000 litres/min at full reservoir pressure were encountered. These were completely eliminated during the rebonding of the fissures with the RODUR technique.

### b) Grouting of the Foundation Rock

It would seem that case histories dealing with remedial rock grouting for seepage control under concrete dams are not so common as those describing similar treatments under embankments. If this is in fact a true reflection of the relative levels of activity, possible explanations could include:

- grout curtains for concrete dams are usually an integral part of the design, and the only primary defense against seepage. They are therefore executed intensively to the highest engineering standards.
- Excessive uplift pressures can be alleviated by drainage curtains drilled from galleries within the dam. This is not so easily conducted under embankments.
- Site selection and preparation initially tend to be more critical to accommodate the higher stresses imposed by concrete structures.
- Seepage under or around a concrete dam may be more easy to tolerate (assuming uplift is not a problem), as there is no danger of piping fines from the core or contact of the impounding structure.

In any event, case histories from American practice are rare and, excluding the early work on Hoover Dam (18), appear to concentrate on the problem of seepage induced in karstic limestone terrains. Examples from overseas are therefore also reviewed to illustrate current practice and expertise. For a comprehensive state of practice review of rock grouting technology, the reader is referred to the recent book by Houlsby (11). Basically he identifies rock grouting by descending stages, ascending stages, and by the new MPSP method (37). The use of descending and ascending staging has been clearly effective where the rock is competent and where the hydrogeological conditions have permitted classical injection methods and materials. The work (38) to seal preferential seepage paths in potentially soluble geology under the Auxiliary Spillway at Tarbela Dam, Pakistan, is a particularly lucid illustration of this approach. The MPSP method, in contrast, has proved of exceptional value in "awkward" geologies, such as the "sugary limestone" of the Right Abutment of Tarbela.

The other major advance in sealing rock masses under existing concrete dams is one of materials. Hot bitumen had been used since the early 1920's to stop massive inflows, but only in the last twenty years or so has technology advanced to properly take advantage of the technique. To put the problem in perspective, the Tennessee Valley Authority have 21 of 30 dams built on potentially erodible karstic terrains and have long been a user of hot asphalt injections backed with cement (36). The work at Great Falls Dam and Tims Ford Dam are excellent examples. More recently, Ontario Hydro have similarly sealed leakages of about 20,000 litres/min under full hydrostatic head in large fissures at Stewartville Dam, ON (39). This work was carried out quickly and cheaply, following years of futile and expensive attempts with upstream blanketing and conventional cement grouting. Subsequent exploration holes revealed good bond between the asphalt-cement-rock system, and the sealing is regarded as a permanent solution.

### *Embankment Dams*

The treatment of embankment dams may involve both rock grouting, as referenced above, and soil grouting techniques. In some ways, soil grouting is more complex and less precise given the tremendous range in both influential soil properties, and in grouting methods and materials. As a guide, papers by Naudts (27) and Bruce (41) will serve to lend perspective to the myriad of excellent books (e.g. Karol, 13), and conference proceedings (e.g. 15). However, one should note the caveat made by Von Thun (40) in conjunction with his analysis of the Quail Creek Dike failure in 1989. This was an occasion when grouting was not effective: although it remedied the symptom of the problem (excess seepage), it did not resolve the real problem (the potential for embankment materials to pipe excessively due to lack of contact treatment during original construction and a tendency for gypsum dissolu-tion). This must always be a critical point in evaluating the nature of the remediation proposed.

In connection with seepage control, the two basic types of soil grouting involved are:

- permeation: where grout is placed into the pre-existing pores while preserving the virgin soil structure, and
- jet grouting: where cement grout at very high pressure is used to simultaneously erode and mix with the soil. The cutting effect of the grout is often enhanced by combinations of air and/or water.

A third major category of soil grouting - namely compaction grouting - does not primarily cause reduction in permeability, and so is not discussed in this section. However, its ability to densify soils in situ has been impressively exploited to combat liquefaction potential, and further discussion is provided in Section 4, below.

The fourth major category - hydrofracture or claquage grouting - also has no relevance for seepage control in this context. Overall, it would seem that the question of drilling and grouting the core of an existing embankment dam is a delicate and emotive issue. There are those who fear that hydrofracture of the core will result from the pressure of the flushing media used in the drilling, or from the grouting pressures exerted during injection. These fears typically lie in the minds of engineers who do not appreciate the significance of recent advances in the seven basic overburden drilling techniques, especially the duplex variants (42), or do not enforce strict interim limitations on fluid grout volumes as well as pressures. Paradoxically, many of these engineers see no threat when commissioning concrete diaphragm wall cut-offs, wherein bentonite filled trenches of several hundred cubic meters volume have to be excavated through the very same core materials.

In this context, the recent experience at Mud Mountain Dam, WA, is a fascinating example (19, 43). There was a pressing need to seal the silty sand core of the dam, a structure 210m long and a maximum of 127m in height. The favored solution was a concrete diaphragm wall comprising 67 panels 1m thick and 7m long with a maximum depth of over 130m. However, construction was soon interrupted by massive losses of bentonite into open zones in the core. These fundamentally cracked the core longitudinally and created a network of other fractures thus potentially compromising the integrity of the embankment and the ability to continue the repair. Slurry losses exceeded 4000m$^3$, with as much as 800m$^3$ being lost in a matter of a few minutes in certain panels. The diaphragm walling was therefore suspended. It was then decided to carry out a massive grouting operation to repair the core - to permit the continuation of the diaphragm walling. Tube à manchette techniques were used to "recompact" the core. Two rows of holes, 1.8m apart, and totaling 6000 lin. m of drilling, were installed. Over 3600m$^3$ of cement-bentonite grouts were injected, some with silicate to accelerate set in especially severe locations. The diaphragm wall has since been completed without further incident.

In summary, it is clear that modern drilling and grouting techniques, methods and materials can be exploited to seal the cores of existing embankments efficiently, economically and without danger to the stability of the structure. In detail, the following remedial case histories can be cited in support of this thesis regarding embankment dams on rock foundations:

- Two dams in Eastern Canada (44). Sealing of core and foundation rock with cementitious materials and classic ascending stage methods.
- Ash Basin 2 in Pennsylvania (45). Sealing of core and foundation rock with both cementitious and acrylate grouts using conventional split spacing.
- St. Mary Dam, Alberta (46), and Gurley Reservoir Dam Co. (47). Sealing of bedrock by conventional staging methods and cementitious grouts.
- Anonymous (48). Sealing of bedrock with chemical grout injected by simple end of casing methods.
- King Talal Dam, Jordan (49, 50). Sealing of abutment of massive dam using state of practice cementitious and chemical grouts.

For the rarer breed of embankment dams on alluvial or glacial foundations, the following examples can be cited:

- Tarbela Main Embankment Dam, Pakistan (38). Location and sealing of major flow paths by end of casing injection with cementitious grouts. (Also at Wells Dam, WA, more recently.)
- Stewart's Bridge Dam, NY. Sealing of major flow paths by the same principles, with surprisingly effective results consider-ing the contemporary levels of technology (mid 1950's).
- New Waddell Dam, AZ (51). Trial to investigate potential of jet grouting. Subsequently adopted with success on numerous dams worldwide including Brombach (Germany), Villanueva (Spain), Deerfield (USA), and John Hart (Canada) amongst others.

## Settlement Control (Concrete Structures on Rock)

It is common in new dam construction to conduct intensive grouting to relatively shallow depths under the "footprint" of the new dam. This "blanket" or "consolidation" grouting is intended to reduce the overall settlement of the superimposed structure, and to ensure that such settlements are uniform and not differential. The blanket grouting also reinforces the effectiveness of any hydraulic cut-off, as it effectively widens it in the zone of greatest sensitivity. In remedial operations, similar principles can be reapplied where unexpectedly large and/or differential movements have occurred in service, leading to cracking of the structure. In Europe, such problems have been noted in certain high concrete dams, usually of the double curvature thin arch type. Repair programs have strongly featured grouting - sometimes with epoxy resins - as a major element in the rehabilitation (34). In the United States, there have been problems with certain lock structures, founded on bedrock permitting unacceptably large deflections during daily or annual loading cycles.

In addition, structural distress can also be caused by simple washout of founding material. In such cases, the grouting is relatively "low technology" - being intended as a simple void filling operation - even though the execution may involve difficult underwater support efforts by diving personnel. The first example in the following list illustrates the scale such applications can reach:

- Old River Low Sill, MS (52). Infill of over 23,000m$^3$ of scour induced voids with various cementitious grouts.
- John Day Lock and Dam, WA (53). Injection of foundation with classical stage, cementitious grouting methods to increase to uniform levels the elastic response of the bedrock.
- Little Goose Lock and Dam, WA (9). Similar application, with result quoted as "greatly reduced (structural) movements ..., and additional stability to the foundation."
- Savage River Dam, MD (9). Similar application, but in limestone as opposed to volcanics.

## Remedying the Effects of Seismicity

It has been calculated that 650 of our 2000 Federally owned dams are located in highly seismic areas (54). Similar proportions of private and state owned dams are equally threatened: for example in Illinois alone there are now over 30 dams in the major earthquake zone where the New Madrid events occurred in 1811-12. Well constructed earth dams built on competent foundations, and embankment materials generally perform well. However, embankment dams built of hydraulic fill or founded on loose saturated sands have the potential to liquefy. The Corps of Engineers (55) have devoted considerable effort to the study, and concluded that grouting is a very acceptable remedial technique. However, no general approach or method is believed applicable for all conditions or structures, and still Marcuson and Silver (54) advise that "in situ improvements made to dam foundations and embankments are the most challenging aspect of seismic dam improvement." With respect to the potential of grouting technology, liquefaction potential can be reduced by

- densifying the soil - by compaction grouting
- giving "cohesion" to the soil - by permeation grouting
- desiccating the soil - by grouted cut-off
- creating isolated, regular "cells" - by jet grouting or SMW Method (56).

As yet, the fourth generally recognized form of soil grouting, namely hydro- fracture, has not been used. However, developments are underway on the West Coast into so-called "lense" grouting, using fluid grouts reinforced with fibers to provide flexural and tensile strength to grouts in situ. Provided the inherent problems of injection control are overcome, this method could be regarded as having potential in certain circumstances involving soil containment.

The examples listed below all deal with remedial measures, conducted, however, <u>prior</u> to a major seismic event, and therefore designed to mitigate the effects. Grouting also has a key role <u>after</u> such events, to repair the structure and/or secure the dam/bedrock foundation. Although only one recent case in the latter category can be cited from published sources, there are current examples of ongoing work in various "fiery ring" areas of the world, including Iran, USSR, New Zealand, and Latin America.

- Pinopolis West Dam, SC (57, 58). Extensive and very successful test program in which compaction grouting was used to densify a 1.2 - 2.4 m thick loose sand layer 10-12m below the surface, by a factor of over 4 times. The method was subsequently adopted on full scale production works. Note that similar methods did not prove as effective at Steel Creek Dam for geotechnical and practical reasons.
- Laboratory Testing (59). Concluded that even a very weakly cemented (i.e. grouted) sand would require "a very large earthquake loading to liquefy". The concept was also implicit in Bell's description (60) of chemically grouted "thrust blocks" in alluvium at Asprokremmos Dam, Cyprus.
- John Hart Dam, BC (61, 62, 63). Jet grouting used to form hydraulic cut-off under embedded concrete structures and so permit desaturation of soils otherwise prone to liquefaction.
- Jackson Lake Dam, NY (64-67). First use of mechanical mix in place system developed by SMW Seiko. Overlapping "soilcrete" columns up

to 1m in diameter were drilled vertically to form continguous hexagonal honeycomb "cells" of 10m diameter. These then isolated the soil mass under the footprint of the replacement embankment dam into discrete volumes, so preventing general liquefaction while providing, overall, increased lateral stiffness to the mass. The technique was also used to form a hydraulic cut-off, an application recently repeated at Cushman Dam, WA.

- Austrian Dam, CA (68). Embankment/bedrock contact explored and sealed with classical grouting methods following suspected damage during the Loma Prieta Earthquake.

## Final Remarks

This review cites data from 35 dams to demonstrate the proper application of grouting techniques to remedy defects caused by seepage, movement or earthquake susceptibility. The range of rock grouting methods (conventional staging to MPSP system), and soil grouting methods (permeation, compaction, jet and SMW) has been illustrated, as has been the range of materials used (cements to chemicals). Examples have covered both concrete and embankment structures.

Even then, this review cannot hope to be comprehensive in terms of listing and describing all such remedial case histories. However, it is hoped that the framework of the paper will prove to be a durable contribution, which will help put unresearched, or future, case histories in perspective. In this regard, a current task of the USCOLD Foundations Committee in assembling a register of dams rehabilitated by specialist geotechnical construction techniques may well be eased.

Fellow specialists should feel encouraged not only to confidently use grouting to repair dams, but also to publish the results as widely as possible.

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