

# A REVIEW OF SPECIALTY GEOTECHNICAL TECHNIQUES FOR DAM SAFETY

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## ABSTRACT

Both concrete and embankment dams may be threatened by the effects of strong seismic events. An excellent example of the former is the recent repair to Stewart Mountain Dam, an elderly delicate double curvature thin arch dam near Phoenix, Arizona. On this project a novel rock anchoring program was conducted. A second major remedial tool for concrete dams is the RODUR method of structural rebonding by epoxy resins. The paper describes the application of both these very powerful techniques. Embankment dams and their foundation soils can be safeguarded against liquefaction by a rather larger range of techniques including grouting (permeation, jet and compaction), and the SMW mix in place system. Case histories illustrating each principle of repair are presented.

## INTRODUCTION

The safety of existing dams may be threatened by many phenomena both natural, such as floods or earthquakes, and manmade, such as design inadequacies or constructional defects. Increasing attention is now being paid to combatting the effects of seismic events, at a time when larger, more complex new structures are being built on less favorable geologies, and more is being understood about the behavior of older dams and their constituent materials.

In recent years, much has been written about the use of various highly specialized geotechnical techniques for dam remediation. Papers and books have appeared on rock anchoring (Bruce, 1989; Xanthakos, 1991; Bruce, 1993), grouting (Bruce, 1990a; Weaver, 1991; Bruce, 1992) and diaphragm walls and similar

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cut-offs (Bruce, 1990b). However, the intent of this review is to extract from this large pool of knowledge data relevant only to the safeguarding of dams against seismic damage.

The case history of Stewart Mountain Dam is used to illustrate the use of post-tensioned rock anchorages to secure a high, delicate double curvature concrete dam in a potentially seismic area in Arizona. This technique has also been recently used, after the event, to repair a major concrete dam in Iran. Also in relation to such structures, the potential of the resin grouting technique of RODUR is described.

For embankment dams and their foundation soils, a larger range of techniques and principles can be employed. Densification can be achieved by vibroflotation or compaction grouting, and increase in intergranular cohesion by permeation grouting. Dewatering has been effected by diaphragm walls and by jet grouting, while the concept of volume isolation can be illustrated by the mechanical mix-in-place work conducted at Jackson Lake Dam in Wyoming.

A short account of the most apposite applications is given to illustrate their principles and potential.

## CONCRETE STRUCTURES

### Post-tensioned Rock Anchorages

The use of such anchorages for dam stabilization is as old as the technique itself: the first application was at Cheurfas Dam, Algeria, in 1934 (Littlejohn and Bruce, 1977). The typical applications include providing resistance to overturning (Bruce and Clark, 1989), and restraint to sliding or a combination of both (Bragg et al., 1990). In addition there are countless examples of rock anchorages being used in spillway construction, and for rock mass stabilization for abutments, portals and excavations (Hanna, 1982; Hobst and Zajic, 1983).

Most recently, however, a novel seismic application has been executed at Stewart Mountain Dam located on the Salt River 40 miles northeast of Phoenix, Arizona. During the 1920's, when this 205' high double-curvature, thin-arch dam was being built, the significance of effective construction joint clean-up was not fully appreciated. As a result, horizontal construction joints at 5' intervals had a thin layer of laitance and exhibited little or no cohesion. The arch section was therefore not a monolithic structure, as designed, but a series of unbonded blocks held together by gravity and natural arch dam action. Individual concrete blocks would therefore be unstable high in the arch during a major seismic event because of poor construction joint bond, large inertial forces, and separation of the arch along vertical joints. Alkali-aggregate reaction had also attacked the concrete, leading to concrete expansion, surface cracking and

permanent upstream crest movement of 6" between 1930 and 1968. More recent material studies indicated that the concrete still had enough strength and stiffness to support normal loading conditions and, indeed, interior concrete showed trends of healing and gaining strength.

The Government considered the MCE (maximum credible earthquake) to be of magnitude 6.75, 9 miles away, producing an estimated site acceleration of 0.34 g. This seismic event would have been sufficiently major to significantly shake the structure and cause instability of the blocks high in the arch.

In order to restore the structural monolithicism and increase factors of safety during normal and seismic loadings, post-tensioned rock anchors were judged to be the most economic and viable solution. A total of 62 anchors was installed at about 8' centers along the 580' long dam crest, with individual design loads of 550-750 kips. They ranged from 2°30' downstream to 8°40' upstream and from 72-246' long. Each tendon had twenty-two 0.6" diameter strands. A further 22 anchorages, each of 28 strands, were installed at 60° below horizontal through the adjacent Left Thrust Block to resist sliding.

Three-dimensional finite element studies showed that these anchor forces had a very positive effect on the arch by providing additional normal forces across the weak horizontal construction joints and by horizontally compressing the arch. They also added stability by increasing the lateral support. These analyses did show, however, that arch action and lateral support were still lost in the top 40', at times, during the MCE, and that this zone warranted special attention.

The major implications of the site, the structure and the design on crest anchor construction were as follows:

- Drilling: High accuracy drilling was essential as the dam was 5-35' thick and contained drains and other structures (tolerance: 9" in 100'). The drilling method also had to ensure minimal distress to the arch.
- Grouting: Potential grout flow paths through concrete lift joints and in the foundation rock had to be located and sealed.
- Stressing: The tendons were loaded in special sequence across the arch to avoid the danger of local overloads. The structure was also monitored for a 100-day period before the tendons were locked-off.
- Corrosion Protection: To protect the bare strand of the free length during the load monitoring period, but to still allow it to be bonded to the upper 50' of the dam thereafter, epoxy coated strand was specified.

In every aspect, this project was highly successful and

satisfactory, as detailed in various publications including those by Bruce, et al. (1991a, b) and Bruce and Bianchi (1992, 1993).

### Epoxy Resin Rebonding

This is a remedial technique featuring a novel approach to injection theory and practice. Masonry dams have long been grouted to prevent seepage, e.g., Aswan Dam, Egypt (Nonveiller, 1989), as a result of material deterioration or dissolution. However, the repair of a concrete structure fundamentally fractured is a different matter.

Over the last decade many major concrete dams have been structurally rebonded using epoxy resin materials, and associated drilling and injection innovations. Under such conditions, the fissures may contain water, possibly at high pressures and with high flow rates. Equally, there is a need for great tensile and adhesive capacity in the grout, qualities which conventional cementitious or "chemical" grouts do not typically possess. Epoxy resins, appropriately formulated, satisfy these needs as

- they ensure maximum fissure penetration as they are true liquids of low surface tension and not a suspension of solids;
- they are immiscible in water;
- they have controllable, but short hardening/polymerization times, to minimize displacement by flowing water;
- they have an almost constant viscosity until setting;
- they have minimal shrinkage;
- they have high shear strength and adhesion but low elastic modulus;
- they are durable;
- they are chemically stable and non-toxic both during handling and in service.

Examples of successful applications were reviewed by Bruce and DePorcellinis (1991).

## EMBANKMENT STRUCTURES

### Soil Densification

As summarized by Mitchell and Van Court (1992), there is a wide variety of methods which can be used to densify soil, and so raise its resistance to liquefaction. However, many are simply not applicable to the repair of existing embankments, or their foundation since their execution may involve intolerable settlements or vibrations or other practical restraints. Into this category fall deep dynamic compaction, blasting and vibroflotation, although these techniques have proved of real value, in appropriate soil conditions in preparing new sites before construction (or reconstruction) of the dam. In this regard, the work done at Jackson Lake Dam (Farrar, et al., 1990), and at Mormon Island Dam (Stevens, et al., 1992) is of particular interest.

On the other hand, the application of compaction grouting (Warner, 1982; 1992) permits densification without the fear of surface settlement. Compaction grouting therefore has considerable potential - in the appropriate soil and site conditions - and an informative case history was described by Salley et al. (1987) with reference to a test section at Pinopolis West Dam, S.C. The 70' high, 6600' long homogeneous rolled earthfill dam was built in 1940. It is underlain by 4-8' of very loose sand about 12' below the original ground surface. Historically, the Charlestown area has proved seismically active, and studies showed that the sand could liquefy and render the dam unsafe during an earthquake. Various downstream structures were considered to improve the seismic stability of the dam, as well in-situ densification of the loose sand for which compaction grouting was promoted.

Compaction grouting features the injection under pressure of very stiff, low mobility grouts to displace and densify the surrounding soil. In contrast to permeation grouting (in which preexisting pores are infilled with grout) the influence of the grout bulb extends well beyond it, affecting soil volumes up to 20 times the placed grout volume. For embankment grouting, depths are usually greater, grout volumes are larger, and injection rates may be up to 10 times faster. (However, when grouting on a sloping embankment, lateral displacements can easily occur, and may limit the treatment's effectiveness.) Concepts of mix design, and grouting methodology, parameters and analyses are detailed by Baker (1985).

The grouting was conducted from a special test berm 20' high x 44' wide x 150' long built at the downstream toe of the main embankment. This allowed the actual conditions to be simulated without the need to operate initially under an active structure. Instrumentation was installed to monitor porewater pressures and embankment deformation. At this location, the target horizon was 32-40' below the berm's surface. This horizon was classified as very loose - loose, grey silty-fine sand, water bearing, with 10-20% fines and  $D_{50} = 0.3 - 0.6\text{mm}$ .

The Primary holes were installed on a 12' grid, with intermediate Secondaries and Tertiaries. The grout was pumped through 3" id. steel casing at rates of up to 15 gal/minute at pressures typically 300-600 psi. The limiting criterion to grout volume injection was embankment heave of 1" at depth and/or 0.25" at the surface. The former value was later reduced to 0.75" for the production work. Primary hole takes averaged 60 gal/ft, Secondaries 50 gal/ft, and Tertiaries 28 gal/ft. A total replacement volume of 25% was injected overall.

Post grouting tests indicated the following:

- Electric Cone Penetrometer - tip resistance increased from 300 to 1200 psi after Secondaries, and to 1800 psi after Tertiaries.

- Standard Penetration - increased from 4 to 17-25. (Previous studies had shown that a value of 11 was sufficient at the test site to avoid the potential for liquefaction at the downstream toe, and assure a safety factor of 1.25.)

These increases alone suggested corresponding increases in resistance to liquefaction, but even then they "do not adequately reflect increased resistance --- due to large increases in lateral stresses ..."

- Flatplate Dilatometer Test - showed improvements in Constrained Modulus by 10-50 times.

The benefits of compaction grouting were clearly demonstrated in this program, and the technique was used, with minor modifications, in the subsequent full rehabilitation works. As a word of caution, it must be noted that a similar approach was tested at Steel Creek Dam, where Baker (1985) ascribes the "reduced effectiveness" to (i) the use of a grout mix in which sand blocked the injection process at too low a pressure, (ii) the effects of highly plastic fines in the soil which restricted rapid densification, and (iii) the unfavorable (sloping) site geometry.

### Soil Permeation

Clough et al. (1989) noted that cementation can exist in a sand naturally, or can be added artificially. In either case it is known to increase the resistance to liquefaction. They experimented with sand weakly cemented by various types of chemical grouts, and concluded that a saturated medium sand with 2% cement content and an U.C.S. of only 14 psi was stable to the point that it would require "a very large earthquake loading to liquefy". They also found that the unit weight of the soil only had a significant impact on liquefaction potential at low strengths (less than 60 psi).

The inference is clear, therefore, that permeation grouting with even relatively weak grouts is technically very effective. However, such grouts are typically unstable in the long term, and may still prove expensive to place, when the drilling and injection costs are included. No case histories of permeation grouting for primary liquefaction control have been found, although the concept is implicit in Bell's description of chemically grouted "thrust blocks" in alluvium at Asprokremmos Dam, Cyprus (1982). Recent developments in very penetrative and economic cement grouts (DePaoli et al., 1992a and b) may make this approach more attractive in the future.

### Soil Dewatering by Positive Cut-off

Imrie et al. (1988) described the use of a seepage cut-off to desaturate soils at the John Hart Dam, B.C. This 130' high dam on the Campbell River, Victoria Island, was completed in 1947. It was not specifically designed for earthquake resistance and

the foundation soils were saturated and prone to liquefaction. The original design allowance for 0.1g maximum seismic horizontal acceleration compared with the revised estimated m.c.e. acceleration of 0.6g. The twin needs to keep the reservoir full (for generation), and to maintain high water quality in the reservoir and the river led to the concept of an in-situ cut-off wall to desaturate the fine-medium sands of the embankment and the fluvioglacial sands of the river bed. In addition, some soil replacement and densification was also conducted in some other areas of the scheme.

Whereas most of the 1300 lin. ft. of cut-off was formed by conventional slurry trench diaphragm wall, jet grouting was used for the remaining 200'. John Hart Dam thus became the first dam in North America to be rehabilitated with the jet grouting technique, used under and around the embedded concrete structures.

The diaphragm wall specifications called for a permeability no greater than  $1 \times 10^{-6}$  cm/s, a 7 day UCS of 400-1400 psi, and the ability to undergo a minimum of 10% strain without cracking, as verified by the 7 day test. A cement bentonite slurry comprising 12% cement and 4% bentonite (both by weight of water) was developed. The wall was constructed using both rope suspended and kelly grabs to a maximum depth of 95' to tie into a suitably impermeable horizon. Exacting quality control and assurance tests were conducted in both field and laboratory of all the materials used.

Regarding the jet grouting, the one fluid system (Bruce, 1988) was used, featuring a grout injection pressure of 5700 psi. A total of 203 columns, each about 3' in diameter, were formed in two rows, 45' deep, using the same cement-bentonite mix as the diaphragm wall. The jet grouting technique required only small diameter holes to be drilled through the base slab of the concrete structure. Prior to the production work, a field test was conducted in which columns were tested in-situ for strength and permeability before being exposed and sampled for further testing.

All the verification and quality testing of the cut-off confirmed its construction to design standards. Piezometric and pump test data confirmed the effectiveness of the treatment upon completion.

#### Soil Isolation by S.M.W. Seiko Method

Jackson Lake Dam is situated in Grand Teton National Park and was constructed in several stages from 1906 to 1916. It includes a northern embankment of hydraulic fill 4300' long, and 5-50' high, founded on fluviolacustrine and lacustrine sediments comprised of loose saturated gravels and sands with variable fines. Seismotectonic studies confirmed that the Teton fault zone was capable of a magnitude 7.5 event at an epicentral distance from the dam of 4 miles. The studies conducted in 1975 as part of the

Bureau of Reclamation's Safety of Dams Program indicated that the embankment and its foundations were susceptible to liquefaction in this case. A major phase of modifications was put in hand from 1986 to 1988 including demolition of this embankment, and various foundation treatments prior to rebuilding (Farrar et al., 1990; Von Thun, 1988).

Deep dynamic compaction, using wick drains, was successfully and economically used to densify the soil to a depth of 40' in the northern half where the subsequent embankment height would be less than 25'. However, at greater depths in the rest of the area, and for 3950' of cut-off to depths of 110', another technique had to be considered. Originally the idea was that jet grouting could be used to provide both liquefaction resistance and the cut-off, but a proposal featuring the Seiko S.M.W. (Soil Mixed Wall) Method proved superior in terms of cost and time. Although this work was conducted in essentially a "new site", it does equally have the potential for being conducted through an existing embankment. For the treated soil column method to be effective, the adjacent columns had to be fully contiguous, and to have a minimum shear strength of 200 psi.

In principle, grout is pumped down through each of the 2 or 3 hollow stem augers (non continuous) as they are simultaneously advanced and withdrawn to form "soilcrete" columns. 2% of bentonite by weight of cement is used to aid pumpability. The crane mounted augers are electrically driven. Volumetric central batch plants are operated semiautomatically to provide grout at rates and pressures appropriate to each auger's progress (Taki and Yang, 1991).

An initial phase of testing indicated that a cement content of about 200 lb/ft was necessary for a 3' diameter column at a w:c ratio of 1.35. For the production work, double auger machines were mainly used to provide 3' diameter vertical columns to form contiguous hexagonal "cells" to isolate the soil mass against general liquefaction. Triple augers were used for the upstream cut-off and some of the deeper cells. A template was used to ensure the correct cell shape, and a shallow trench was pre-excavated around it to contain overflow or waste.

In the double auger work, all columns were drilled and grouted twice to 100 - 150% theoretical volume to assure intercolumn continuity and contact. With the three auger system, a Primary and Secondary system was used to provide a wall 2' thick composed of contiguous columns with at least 100% grout target volume. In such cases, 70-80% of the grout was injected on the way down and the balance on the way up with reversed auger rotation.

Columns as deep as 75' could be formed in one pass. Originally the waste was 15-30% of the total grout injected volume, and so early in the work the target volume was reduced to 150 lb/ft at w:c = 1.25.



Overall, the deep grid was completed over a "footprint" of 220,000 sq. ft., to an average depth of 70' to provide a stabilized foundation block of about 570,000 c.y. This involved 430,000' of columns and 40,000 tons of cement. The cut-off wall measured 250,000 sq. ft. over a length of 4000' and consumed 8200 tons of cement.

Throughout the work, an aggressive qa/qc program of tests was conducted on wet samples, and on cores from set column material. The average core strength was just under 700 psi although it was noted that "coring of hardened column material and evaluation of core strength is difficult due to several factors including the length of time and strength before coring can commence, presence of gravel or unmixed soil in a column, problem of staying in a column for entire length, low tensile strength of treated soil, stresses imparted to core during drilling and the effects of handling core material."

Clearly the effectiveness of the honeycomb grid treatment - as opposed to an overall mass grouting - will only be truly demonstrated in the course of a major seismic event, although the work has apparently been constructed to design parameters. The overall effectiveness of the cut-off wall is still being evaluated by full scale areal tests including piezometers and seismic tomography.

#### FINAL REMARKS

Marcuson and Silver (1987) note that "in-situ improvements made to dam foundations and embankments are the most challenging aspect of seismic dam improvement". As demonstrated in this review there is a large number of specialty geotechniques which can be used to secure both concrete and embankment dams. However, it would appear that more is generally known about the practicalities of the techniques themselves than of their possible or real degree of improvement. This aspect of the work is perhaps the most challenging to the contracting community.

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