SEALING CRACKS IN CONCRETE DAMS TO PROVIDE STRUCTURAL STABILITY

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Sealing Cracks in Concrete Dams To Provide Structural Stability

A crack repair system developed in Spain has been used with good results on at least ten major dams in the U.S., Europe, and Asia. The epoxy resin system provides long-term re-bonding of cracked concrete structures.

By Donald A. Bruce and Pietro De Porcellinis

Cracking or fissuring in any concrete structure is always troublesome. When the structure is a major dam with people and property located downstream, cracking becomes a matter of great concern. The typical approach to crack repair is to fill the fissures with some type of grout to stops leaks. To strengthen dams structurally typically involves installing post-tensioning anchors or placing a buttress downstream of the dam.

Several grouting materials are now available that, in addition to sealing fissures, can actually re-bond cracked concrete structures. We believe these materials may offer a viable alternative in some situations to the traditional and more expensive methods of repairing structures using construction techniques. Given the fact that many dams in North America are aging and in need of rehabilitation and repair, these grouting materials may offer much promise to the dam safety community. In the last 13 years, a system using one of these materials, the RODUR method, has been applied in crack repair projects for at least ten major concrete dams throughout the world. To date, the repairs have been completely successful.

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An Historical Look At Crack Repair Methods

For several decades, it has been standard practice to fill major fissures by injecting cement-based grouts, and to fill smaller aperture fissures with "chemical" grouts such as silicates, phenols, and acrylates. In the last 20 years, specialist repair contractors have been using various types of polyurethane grouts to fill small, concentrated fissures.

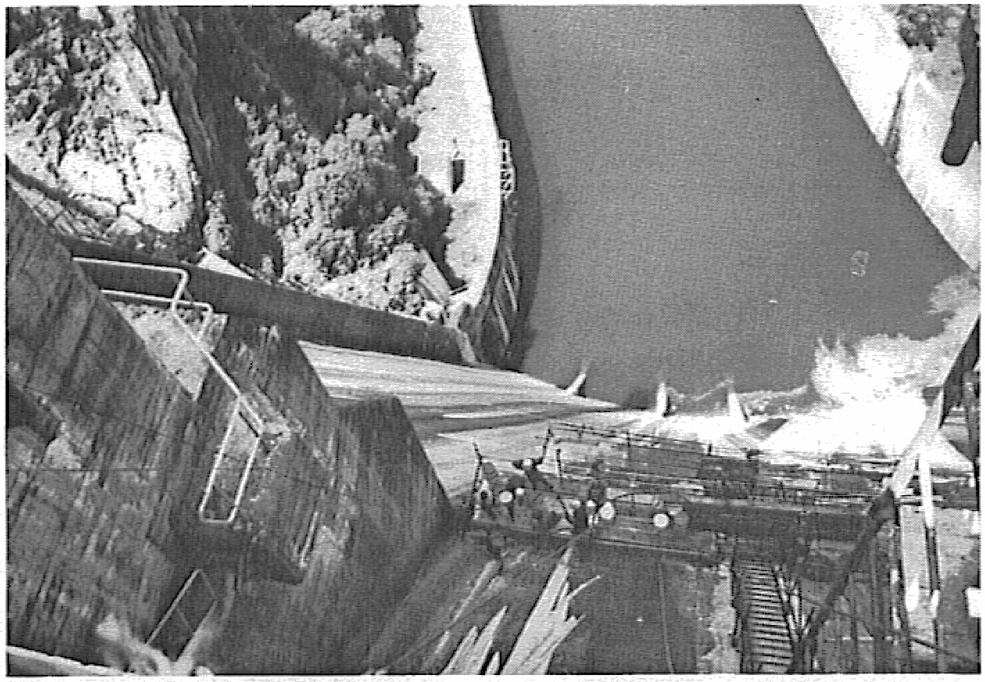
Polyurethane grouts interact chemically with the water to stop the flow. These applications have produced mixed results. Regrouting has often been required because the brittle nature of the polyurethane is incompatible with the tendency of the structure to continue straining. And, attempts at regrouting sometimes have been unsuccessful due to the original inefficient repair using the wrong material—regardless of how conscientiously the regrouting was executed.

In addition, there are practical difficulties in injecting polyurethane grout when site conditions prevent substantial drawdown of the reservoir. For example, the inflow of cold water at high velocity and pressure interferes with the grouting process, and can cause segregation, dilution, and displacement of the grout. In addition, without the reservoir being drawn down, grouters find it difficult to match grout properties to the often irregular fissure geometry. The water also prevents grouters from using high injection pressures.

In the late 1970s, the Spanish government was faced with a structural crack repair job on a dam that presented several limitations, making the use of polyurethane grout unfeasible. The reservoir behind the El Atazar Dam, a 134-meter-high double curvature arch dam, provides the principal supply of drinking water for Madrid. Because critical water storage volumes had to be maintained, the reservoir level could not be significantly drawn down.

The government hired the engineering firm of Cimentaciones Especiales S.A. Procedimientos Rodio (Rodio) in Madrid to come up with a repair solution. After an unsuccessful search for already available technologies that would be suitable for this particular repair, Rodio's engineering team decided to develop a new type of grouting concept.

The new concept, called RODUR, has been used to successfully repair structural cracking at more than a dozen dams, both old and new, throughout the world. Although the



The drilling program at the San Esteban Dam was conducted mainly from fixed scaffolding on both faces of the dam. Some drilling was also performed from the galleries to minimize hole lengths. RODUR series resin was then injected into the drilled holes.

system, which features the use of epoxy resins, is effective at eliminating seepage, its primary role is to re-bond dams that are experiencing fundamental structural fissuring. The RODUR resins, featuring a special combination of fluid and set properties, can be injected efficiently into even the smallest fissures. Once injected, the resins have a relatively quick setting time. They provide a strong, long lasting adhesion to the concrete, resulting in long-term re-bonding.

A Review of the RODUR Grouting System

In essence, the RODUR System is a process to follow for fundamentally re-bonding concrete dams that are cracked. The process has three steps: analysis and research; materials selection; and performance control. Some sort of step-by-step approach is typical in most grouting programs; however, the RODUR system ensures that the steps are applied systemically and accurately.

Holes drilled upstream of the lower gallery of the Santeetlah Dam intercepted individual flows of up to 400 liters per minute at full hydrostatic head seeping through joints. The fissures intercepted by the holes were subsequently sealed with epoxy resin using the RODUR system.

Analysis and Research

When repairing a dam using the RODUR process, the first step is to make every possible effort to understand the cause of the cracking problem. Typically, engineers for the dam owner, a consultant, and the contractor will conduct a detailed review of all existing geological, construction, and behavioral data. Depending on what they discover during this review, the engineers may execute an exploration (coring) and monitoring program.

Materials Selection

The RODUR system makes use of a "family" of epoxy resins that provide a wide range of initial viscosities and polymerization times. The proprietary resins are manufactured by a limited number of specialized formulators. From this family of resins, a specific epoxy can be formulated for each particular situation.

Regardless of the specific formulation, every resin in the RODUR family shares certain properties. For example, every RODUR resin is a true liquid and not a suspension of particles, which would be subject to dilution and washout under typical injection conditions. The resins also harden as soon as practical (within 20 to 50 minutes) after injection to limit and control flow distances. And, the viscosity, which reflects the anticipated fissure width, is reasonably constant and controllable until hardening.

In addition, every resin used in the RODUR process has minimal shrinkage, is durable, and can be easily and safely handled with minimal environmental problems. The resin is usually required to bond efficiently to wet surfaces under high hydrostatic or dynamic heads often in low temperatures. Therefore, it must have high tensile and shear strengths. And, it must have as low a surface tension as possible to ease penetration into fine fissures. Finally, it is usually advantageous for the resin to have an elastic modulus significantly less than concrete so that the resin can accommodate the movements of the dam without cracking or losing bonding.

Performance Control

During the actual treatment, engineers continuously monitor the performance of the grout and the structure. In this way, they can vary the

Table 1: Summary of Major Dam Repair Projects Involving the RODUR Method

Year(s) of Repair	Site and Location	Structure	Dam Crest (m)	Dam Height (m)	Problem	Grout (kg)	Owner	Notes
1978-1980	El Atazar Dam, River Lozoya, Madrid, Spain	Double Curvature Arch Dam for Water Supply	484	134	Failure of upstream joint sealant leading to development of massive fissures (3.5 to 8.5 mm wide) throughout dam.	90,000	Canal De Isabel II, Madrid	Sealed under 90 meters of head and high flow.
1980	Paradela Dam, River Cavado, Portugal	Concrete-Faced Rockfill Dam for Hydroelectric Generation	540	110	Sealing of joints between facing panels.	1,000	Electicidade de Portugal, Porto, Portugal	
1980-1983	Mequinenza Dam, River Ebro, Catalonia, Spain	Concrete Gravity Dam for Hydroelectric Generation	470	146	Differential settlement of foundation rock due to power plant structure led to cracking of dam, encouraging further deterioration by alkali-aggregate reaction.	50,000	Empresa Nacional Hydroelectric Del Ribargozona, Barcelona, Spain	Upstream layer of concrete grouted from vertical holes.
1981-1983	Zeuzier Dam, River Lienne, Switzerland	Double Curvature Arch Dam for Hydroelectric Generation	256	156	Settlement of foundation rock caused major concrete fissures especially in lower part of structure.	150,000	Electricite de La Lienne SA, Sion, Switzerland	
1981	Cabril Dam, River Zezere, Portugal	Very Thin Double Curvature Arch Dam for Hydroelectric Generation	290	132	Multiple fissuring of upper section of dam resulting from nature of design of crest works.	18,000	Electicidade de Portugal, Porto, Portugal	Cracks and vertical contraction joints resin grouted.
1982 and 1989-1991	Koelnbrein Dam, River Malta, Kaernteu, Austria	Double Curvature Arch Dam for Hydroelectric Generation	626	200	Multiple fissuring in bedrock and near foundations due to design in U-shaped valley.	11,000	Oesterieichische DrauKraftwerke AG Klagenfurt, Austria	Resin grouting of concrete and bedrock. One of the highest dams of the type.
1982-1983	Zillergruendl Dam, River Ziller, Austria	Double Curvature Arch Dam for Hydroelectric Generation	506	186	Fissuring of dam due to compression of bedrock.	3,000 in rock plus 6,500 in dam	TauernKraftwerke AG Salzburg, Austria	Resin used in rock grout test and for dam fissures.
1986-1987	San Esteban Dam, River Sil, Orense, Spain	Concrete Gravity Dam for Hydroelectric Generation	295	116	Exploitation of vertical and horizontal construction joints promoting an alkali-aggregate reaction.	171,000	Iberduero SA, Bilbao, Spain	5,300 square meters in 22 joints treated. Also, upstream face applied.
1988-1989	Major Dam, River Furat, Turkey	Double Curvature Arch Dam for Hydroelectric Generation	462	175	Differential compressibility of rock in abutments leading to massive tear fissure throughout the dam.	55,000	Devlet SU Isleri, Aukara, Turkey	Treatment of new dam.
1988	Santeetlah Dam, Cheoah River, Robbinsville, North Carolina, U.S.	Concrete Gravity Dam for Providing Water for Hydroelectric Generation	320	65	Exploitation of vertical and horizontal construction joints leading to severe seepage volumes and uplift pressures.	7,200	Tapoco Inc., Alcoa, Tennessee	First North American application.

grouting parameters (preset after the analysis and research stage) during the treatment to optimize the procedure.

The System at Work

As of the end of 1988, the RODUR method had been used to execute ten major concrete dam repair projects throughout the world. Table 1 provides details about each of these repairs. The method is currently being used in other ongoing repairs. The method also has been used to repair several other concrete structures for nuclear generation and dam appurtenances such as spillways and penstocks.

A summary of the repair work on two concrete gravity dams—the San Esteban Dam in Orense, Spain, and the Santeetlah Dam near Robbinsville, North Carolina—provide good examples of how the RODUR method seals cracks and provides structural bonding.

San Esteban Dam

San Esteban Dam, a 115-meter-high, 205-meter-long concrete gravity dam on the River Sil in northwest Spain, is part of a regional hydroelectric scheme. Completed in 1964, the dam is divided into 17 blocks and has three longitudinal galleries at different elevations.

During deformation monitoring in the first step (research and analysis) of the RODUR process in 1986, engineers confirmed a progressive upstream crest movement at the rate of 1 millimeter a year. The greatest movement was at the abutments. An examination of the joints near these areas indicated irreversible openings and a relative

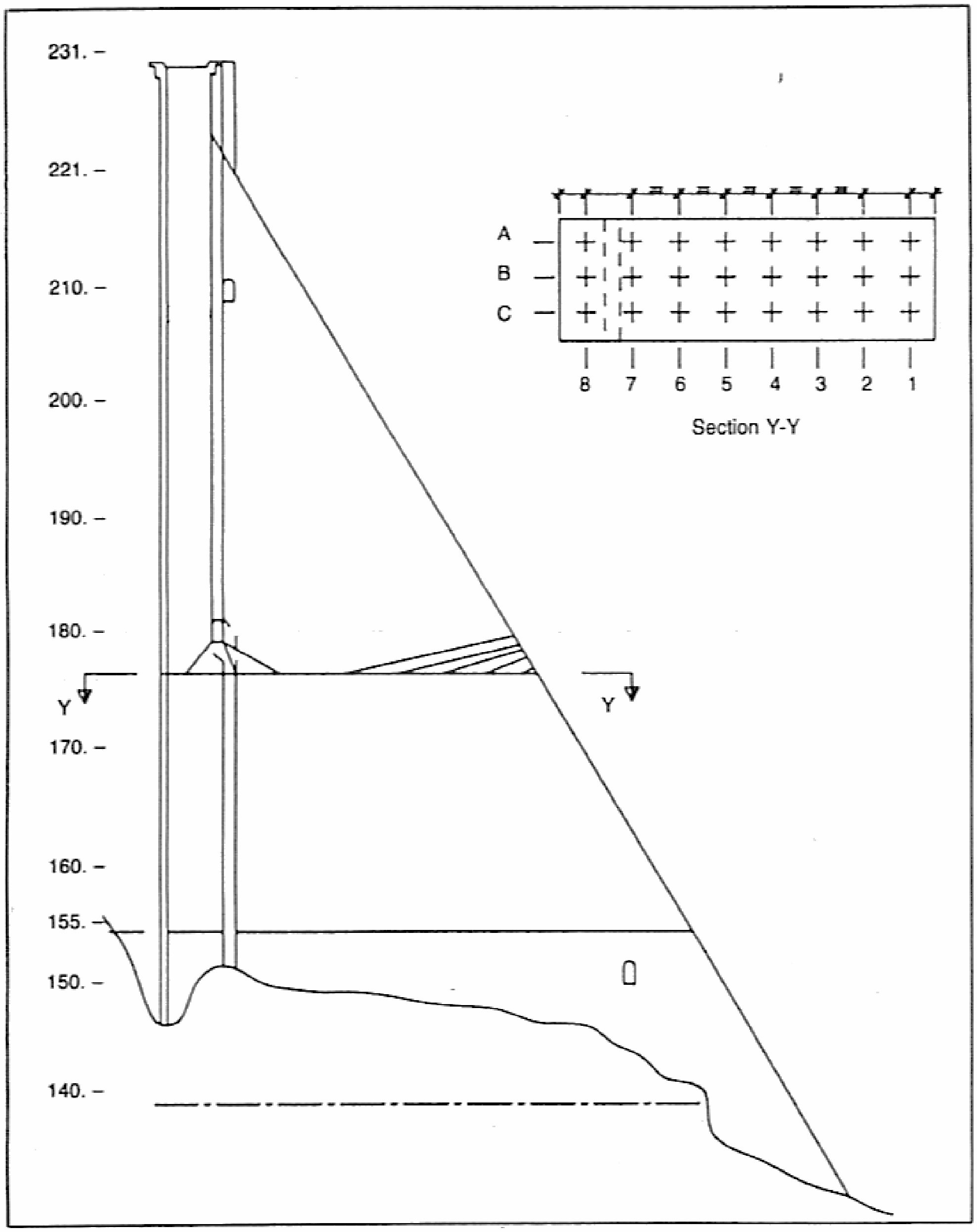


Figure 1: The drilling program on the San Esteban Dam consisted of drilling 46-millimeter-diameter holes on a 3-meter by 3-meter grid, as shown in Section Y-Y. Holes were drilled along horizontal lift joint and cross joint surfaces—a total area of 5,370 meters.

lifting of the central part of the dam. In addition, engineers noted seepage on the upper 50 meters of the downstream face associated with lift joints. When the reservoir level was dropped, the engineers found small zones of localized cracking around the lift joints on the upstream face.

Engineers' analyses proved the movement was caused by an alkali aggregate reaction (a chemical reaction among the cement, water, and aggregate in the concrete that causes the concrete to swell from within). Engineers decided to pursue two types of remediation:

—Restore the mechanical integrity of the structure by re-bonding the joints with a RODUR series epoxy resin; and

—Attempt to inhibit the swelling reaction by waterproofing the upstream face of the dam with a composite membrane of fiberglass and epoxy resin. Before the membrane was applied, the dam had to be sandblasted, patched, and primed.

The RODUR treatment commenced with a full-scale trial, which confirmed fissure apertures throughout the dam in the 2- to 3-millimeter range. In addition, the engineers discovered that there were seepage paths called "worm holes" in the concrete and secondary cracking connected to the horizontal lift joints.

Drillers used diamond coring rigs to drill holes for the epoxy resin injection. A total of 5,370 meters of 46-millimeter-diameter holes were drilled on a 3-meter by 3-meter grid. This drilling program is illustrated in Figure 1.

Most of the grouting was conducted at night due to the extremely high daytime temperatures in northwest Spain. Engineers maintained detailed records of grout pressures and volumes per hole to judge the efficiency of fissure injection.

Extensometers were used to monitor fissure openings during injection. Readings from this monitoring showed a limit of movement of 0.55 millimeters. Deflections were only recorded in areas very close to fluid resin locations.

The dam has operated satisfactorily since the completion of the remediation. Seepage has been reduced by 98 percent, and no further relative displacements of cracks or joints have been recorded.

Santeetlah Dam

The Santeetlah Dam, a 65-meter-high concrete gravity dam in North Carolina, provides water for hydroelectric generation. Completed in 1928, the dam was modified in 1930, 1938, 1950, and 1967 to address recurring seepage problems. Both the 1930 and 1938 modifications involved the placement of massive amounts of additional concrete on the gravity abutment blocks, as shown in Figure 2.

During the past 25 years, the dam owner has routinely measured deformation of the dam crest as well as seepage into the galleries. The deformation data indicate that the crest has been ratcheting (moving upstream in a cyclically increasing manner) since the 1930 and 1938 modifications. The seepage volume has increased in a similar manner. In 1987, seepage in the west abutment had reached over 4,000 liters per minute, and was entering the lower gallery at higher pressures and over larger areas than ever before. In addition, seepage from the downstream side of the gallery was also apparent.

Through investigation of old construction records, engineers discovered that the construction techniques used for the 1930 and 1938 modifications did not provide a structural connection between the old and new concrete, except near the crest. Therefore, the engineers suspected that the seasonal thermal expansion of this added concrete was pushing the crest vertically up and horizontally upstream. The steady increase in ratcheting was attributed to permanent

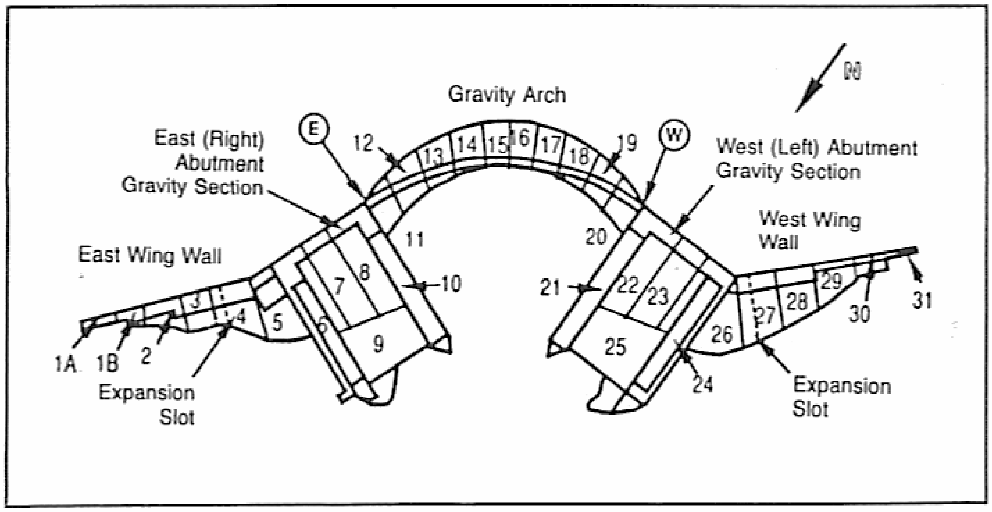


Figure 2: Modifications to the Santeetlah Dam after initial construction involved the placement of massive amounts of concrete on the gravity abutment blocks (blocks 6 and 10 on the east abutment and blocks 21 and 24 on the west abutment). Later modifications added concrete to blocks 7, 8, 9, 22, 23, and 25, and prestressed rock anchors in the wing walls.

displacements in each seasonal cycling due to slip along the interface between original and additional concrete. These upward deformations also opened construction joints seasonally, introducing the possibility of concrete leaching.

The treatment was concentrated on a 23-meter-long section in the most critical area comprising blocks 23 and 24 (see Figure 2), and was conducted from within the 2.4-meter by 2.2-meter lower gallery, which runs about 3 meters above the foundation. Fans of primary holes, up to 6 meters long, were cored at regular intervals upstream from the gallery to investigate the suspect horizontal lift joints about 1.5 meters vertically apart. The primary core holes confirmed that water seepage was only traveling through the joints: the concrete itself was structurally sound.

After all the primary holes were drilled and the data carefully reviewed, the contractor, Nicholson Construction of America, commenced the epoxy resin program. Nicholson selected the particular RODUR resin for the site based on observations of fissures and water flow patterns at the Santeetlah Dam. The resin was injected through disposable packers fixed in each hole that are designed to accept the high pressures the grout may require. Grouters would wait for the resin to travel to and connect with the next hole, and then injection would be transferred to the packer in that hole. This method promoted continuity of the resin filling of each joint.

A secondary phase of drilling and grouting was conducted to demonstrate this continuity, and to permit "tightening up" of especially difficult areas. Resin thicknesses of up to 10 millimeters were found, illustrating the actual aperture of the joints. Verification holes drilled at the end of the treatment process also confirmed the penetration of the secondary grout into micro fissures.

The strong water flows from the reservoir into the gallery encouraged the flow of resin in the same direction, and no evidence of resin traveling into the reservoir was recorded.

During the crack repair using the RODUR method at Santeetlah Dam, 59 drilled holes were injected with a total of 7,170 kilograms of resin.

By the time the repair was concluded, the total flow into the grouted section was about 120 liters per minute—virtually all of which was entering the gallery through vertical roof drains that intersected the fissures well above the levels that had been grouted. The concrete of the upstream gallery wall had begun to dry out, and flows from secondary longitudinal roof fissures and from the downstream gallery wall had been eliminated. This level of performance has continued to date, even when the reservoir was recently at its maximum level for the first time in several years.

Possibilities for the Future

Clearly, the RODUR method or other similar types of epoxy resin programs are not going to be the best or most economical grouting choice in every dam repair case. For example, the method cannot compete economically with water reactant polymers in simple leak sealing operations. However, given the fact that more and more dams are being rehabilitated, the technique offers real potential in the structural repair of conventional and rolled concrete dams that need to be grouted under adverse physical and hydrological conditions. □

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