THE RODUR PROCESS OF CONCRETE DAM REPAIR: A RECENT CASE HISTORY

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SYNOPSIS. The RODUR Process of repairing major concrete structures has been used with remarkable success over the past decade. During that time, 11 high dams alone - from 65 to 200 m high- have been sealed and bonded, often in the presence of full hydrostatic head and high fissure water flows. Recently the first application in North America has been concluded, and this project's description illustrates some basic principles of the process described in the first part of the paper.

1. INTRODUCTION

The fissuring of any concrete structure is always a matter of great concern. When the structure in question is a major dam regulating drinking water or irrigation supplies or permitting electricity generation the problem is especially troublesome and highly sensitive.

The cause of the cracking is usually difficult to discern and often incompletely understood. For example, foundation or abutment performance may be different from that projected, or the dam itself may behave in a non monolithic manner. This may happen when dams of novel concept are built on sites of complex geology. There may be transient processes at play such as heat transmission (a consequence of thermal variations or heat dissipation during concrete curing) or pore pressure development (resulting from water filtration through the dam in service). Equally there may have been intrinsic flaws in the construction of the dam itself, such as poor concreting practices (for example, excessive water cement ratios) or the use of aggregates and cements capable of initiating the expansive alkali aggregate reaction process. Depending on their cause, the fissures may appear as early as first impounding, or may develop after years of apparently successful performance. The presence of cracks implies the action of tensile - or, more rarely, shearing - stresses of magnitude greater than the concrete material strength. Such cracks establish planes of discontinuity within the dam, and, if connected to the upstream face, will markedly modify the dam's integrity and performance.

It has long been standard practice to attempt to fill large fissures by injecting cement based grouts, and the smaller fissures with other conventional preparations such as silicates, phenols or acrylates. These attempts have met with mixed results, and have often had to be repeated at frequent intervals due to the brittle nature of the grout being incompatible with the design of the structure demanding continuing intra structural movements. There are also major practical difficulties in actually executing the works under conditions in which substantial draw down of reservoir level is simply not possible due to economic, environmental or practical reasons. These include 1) the flow of water at high velocity and pressure, 2) segregation and dilution of the grouts, 3) matching grout particle size to the often very irregular fissure width and, 4) the need to avoid using high injection pressures with conventional grouts of long setting times.

Clearly the proper treatment of the fissures must follow an assessment of the causal factors. Decisions can then be made with respect to 1) the ease or practicality of injection, 2) preferred characteristics of the hardened grout, 3) the desirability of bonding across the fissure and 4) if it is feasible to exploit further the fissures with the grout, in order to introduce new compressive stresses in the structures to hopefully compensate the tensile stresses that produced the fissures initially. However, in certain cases it may be difficult to eliminate the tensile stresses for all possible combinations of loads acting on the dam. Then, when the treatment is complete, new fissures may well appear nearby (if the causes of the cracking have not been eliminated), or in other locations or directions (if new tensile stresses occur in response to a changed load situation).

Overall, therefore, from the operational viewpoint it is of prime importance to decide the quantity of grout to be used, as well its strength and to a lesser extent its deformability. Such repairs are in a sense "irreversible": an inefficient repair attempt with the wrong material will greatly reduce the success potential of any subsequent attempt at treatment, no matter how conscientiously executed.

Over the last decade the RODUR process of concrete dam repair has been applied by the RODIO Group with remarkable success. In essence, every attempt is first made to try to understand the cause of the problem. This involves careful review of geological, constructional and behavioral data, often as a basis for executing a new campaign of exploration (by cored holes), and additional monitoring. Initial decisions can then be made with respect to the choice of the grouting material. The fluid properties of the grout, the nature of the fissures and the characteristics of the structure then dictate the initial grout hole design and the sequencing of the repair operation. In addition, the performance of the grouting and the structure are continuously monitored during the works, so that adjustments to working parameters can be made in a timely fashion. This intense monitoring and flexibility of response are keystones of the RODUR approach. The RODUR process has been used for both water sealing and structural bonding, in a variety of high dams including gravity, gravity-arch and double curvature.

This paper reviews briefly aspects of material design and injection theory prior to describing in detail a recent major case history in the United States. This particular project featured the technique as a method or repairing the dam itself: RODUR can also be used to repair the foundation rock if required.

2. INJECTION MATERIALS

In the majority of cases, the following properties are sought of the grout:
(1) It must be a true liquid, and not a suspension of particles, in order to have the best chance of filling comprehensively the fissures, even though the surfaces may be irregular and the aperture small.
(2) It must be immiscible in water.
(3) It must harden as soon as possible after injection to limit flow from the injection point.
(4) It must have a reasonably constant and controllable viscosity till hardening, suited also to the environmental conditions. This viscosity must also reflect the fissure width anticipated.
(5) It must have minimal shrinkage.
(6) It must have good durability.
(7) It is usually required to bond efficiently to wet surfaces, under high hydrostatic or dynamic heads, often in low temperatures, and so have high tensile and shear strengths.
(8) It is typically advantageous to have a modulus of elasticity significantly less than the concrete.
(9) It must have as low a surface tension as possible in order to ease penetration into fine fissures.
(10) It must be easily handled, with minimal environmental problems.

The distance between the grout holes intercepting the target fissure is then chosen to reflect the grout parameters, the radius of action that can be anticipated, and the injection pressure to be applied. This flow pressure depends mainly on the geometry of the fissure, the grout viscosity and the rate of grout flow anticipated.

The RODUR process is based on the use of various types of synthetic epoxy resins. Depending on their formulation, such resins can be provided with a wide range of initial viscosities, which remain constant until the point of polymerization. This time of reaction can be preset. Figure 1 illustrates the influence of temperature on the dynamic viscosity.

For any given application, the choice of a particular resin depends on the factors outlined above, as well as the proximity of the grout hole to the open boundary of the fissure (to avoid wasteful and premature loss of resin). Furthermore, after several test programs it became clear that the efficient sealing of a submerged fissure in adverse conditions demands that the injected grout be kept motionless while being subjected to compressive stresses during the setting process. The impossibility of maintaining the pressure mechanically by pumping (because of the short pot life of the resins) and the need to prevent emulsification during the fluid stage further combined to dictate the use of relatively high viscosity grouts.

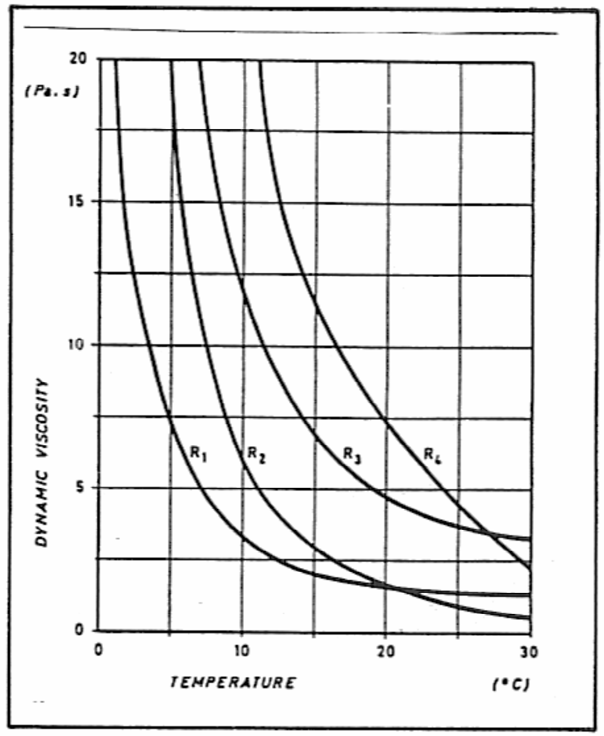


Figure 1. Dynamic viscosity/temperature curves for four typical Rodur resins. (Muzas et al., 1985)

3. THEORY OF FISSURE INJECTION

The general theory of fissure injection has been addressed in informative fashion by numerous authors including Scott (1963), Littlejohn (1975) and Cambefort (1977). Particular attention was paid to RODUR related specifics by Muzas et al. (1985). They wrote that the flow of a viscous material through a horizontal fissure of constant width intersected orthogonally by a circular hole (Figure 2) is equivalent to a centrifugal radial circulation through a porous medium with a notional permeability coefficient k, where

$$k = \frac{B^2 \gamma}{12 \mu}$$

where B = width of fissure (mm)
γ = specific weight of the resin
μ = dynamic viscosity of the resin (Pa.s)

For constant fissure aperture, the theoretical formulation of the problem is simplified, and the pressure distribution can be determined as a natural logarithmic function of distance, itself varying with time. The maximum value of the injection pressure (po) can be related to the characteristics of the grout hole as follows:

$$po = pa + \frac{6 \mu Q}{\pi B^3} \ln \frac{R}{r_o} \qquad (1)$$

where po = maximum injection pressure (M Pa)
pa = water pressure in the fissure. (As the water has far lower viscosity than resin, it can be assumed that this pressure is constant as the water is displaced with a small increase in pressure.)

Q - rate of injection (l/min)
r_o - radius of drill hole (cm)
R - radius of action reached by resin (m)

The value of R is given by:

$$R = r_o \sqrt{\frac{Q.t}{\pi.B.r_o^2} + 1} \qquad (2)$$

where t - time elapsed since the start of injection ($R = r_o$ for $t = 0$).

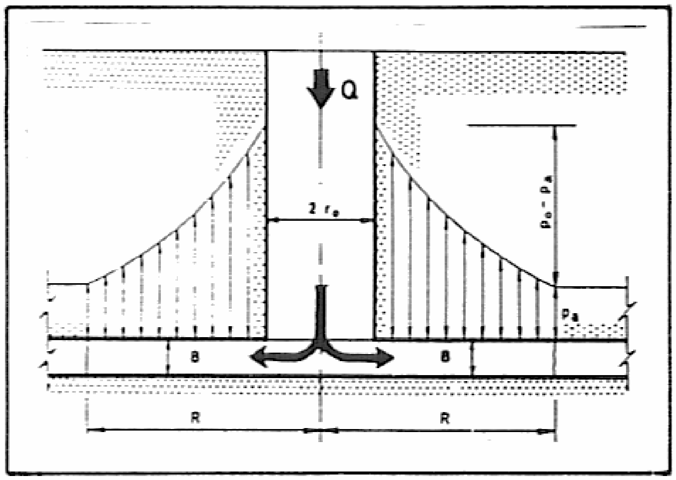


Figure 2. Theory of fissure injection: situation of the resin and pressure distribution at time t. (Muzas et al., 1985)

As illustration, Figure 3 shows the results of equations (1) and (2) for the parameters indicated.

If it is assumed that the fissure opens further as a result of the injection pressures, and that the fissured medium has a coefficient of storage greater than zero, the values of the pressures, and the radius of action reached by the resin are less than those predicted by equations (1) and (2).

It is clear that the viscous resins require relatively high pressures to overcome line losses and encourage flow into fine fissures. Under these circumstances, high pressures are typically not dangerous as then act on relatively small areas with respect to the total fissure surface area or to the overall mass of the dam. In addition, these localized injections do not remain fluid for long periods, and upon setting no longer exert pressure.

When under high pressure, prior to setting, the resin may penetrate the pores of the concrete material. This process can encourage the expulsion of water, so providing dryer and so better conditions for bonding surfaces together.

4: CASE HISTORIES

Summary details of the major dam projects involving the RODUR process are provided in Table 1. In addition, there are five other cases where it has been used in the repair of concrete structures for nuclear generation and dam apurtenances such as spillways and penstocks. Three of these dams have already been described in detail in previous publications, namely Atazar (by Echevarria and Gomez, 1982), Zeuzier (by Berchten, 1985) and Cabril (by Portuguese Working Committee, 1985).

The most recent application has been to repair an old concrete dam in the eastern part of the United States. As will become evident below, the repair has proved exceptionally successful. However the Owner currently wishes to retain the anonymity of the project until the current excellent performance over several yearly cycles has been confirmed. It is therefore referred to, protem, as DAM "A".

4.1. BACKGROUND TO DAM "A".

4.1.1. Introduction

The dam is a 320m long concrete arch structure with gravity abutments and two spillways (Figure 4). It stands a maximum of 65 m above the river bed, and impounds water for hydroelectric generation at another installation.

Construction began on the dam in January 1926 followed by closure in December 1927, and lake filling in April 1928. It would appear that concerns about aspects of the dam's performance arose soon after, and the spillways and the West Abutment were soon reinforced, and again later, in 1938 and 1950, with additional concrete. It is clear from the plan of the dam that the whole structure is not a true continuous arch, with the departure from the classical most marked on the West (Left) Abutment. By far the greatest problems relating to seepage and movements have, not surprisingly, been encountered on this side.

Comprehensive seepage records were historically maintained, and were carefully reviewed during the early and mid eighties. They showed that the amount of seepage was indeed cyclic, being highest in the summer months, coincident with high reservoir levels. By July 1987, however, the seepage had reached its highest volume since the 1940's and was under higher pressure over a greater area of the dam than previously observed. These three factors led to a further study by the Consultants to access the situation and to define remedial measures which could be applied quickly.

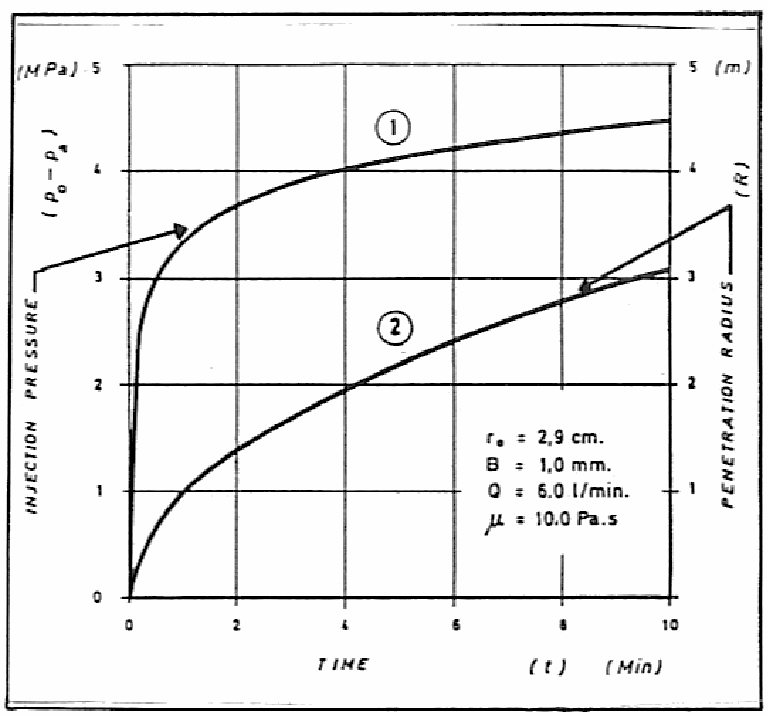
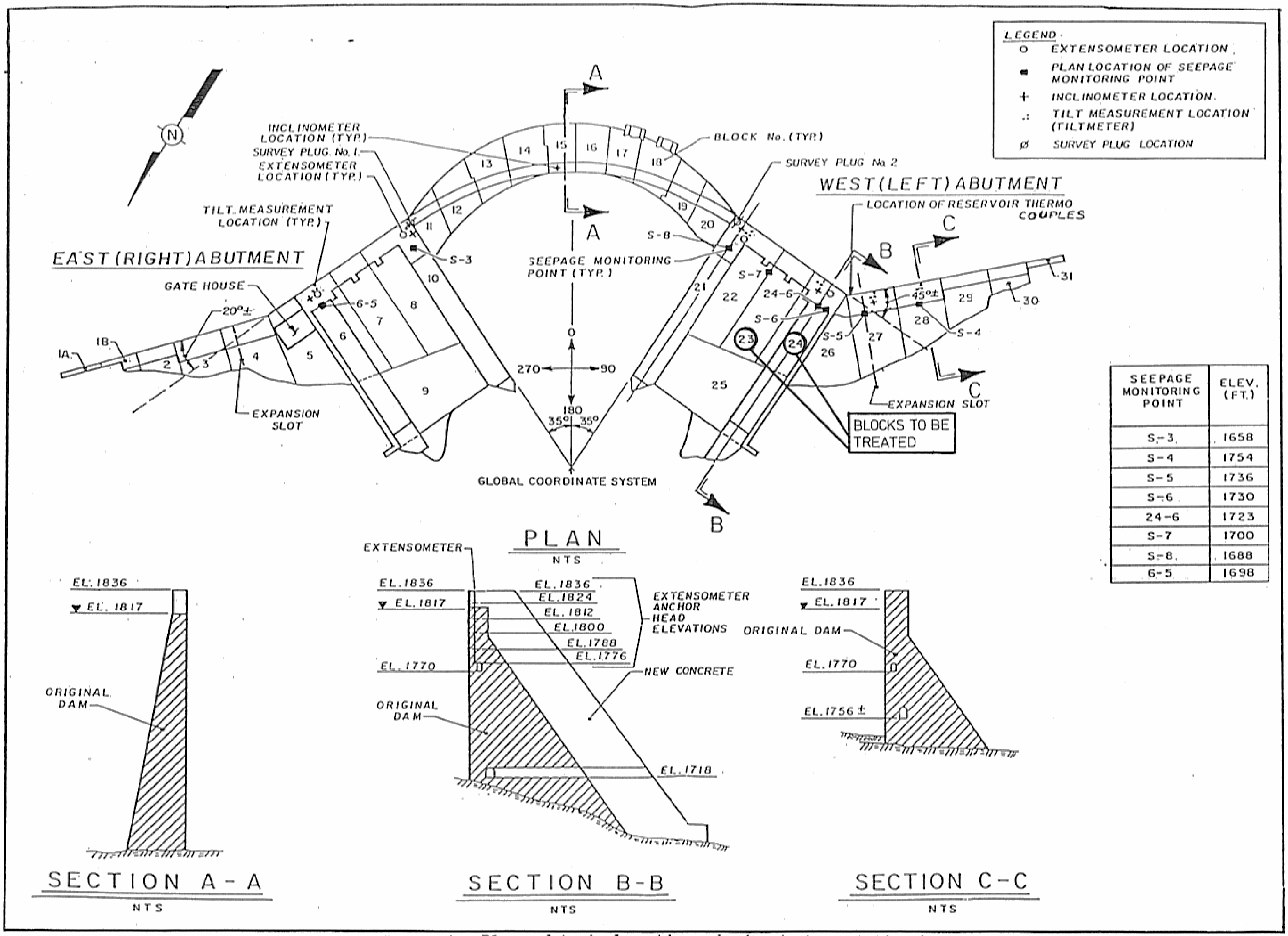


Figure 3. Typical curves based on equations (1) and (2) in text. (Muzas et al., 1985)

YEARS	Site and Location	Structure	Dam Crest (m)	Height (m)	Problem/ Application	Grout (kg)	Owner	Notes
1978 -1980	El Atazar Dam, R. Lozoya, Near Madrid, Spain	Double curvature Arch Dam, for Water Supply	484	134	Failure of upstream joint sealant leading to development of massive fissure ($3200m^2$ - 60% of dam area) through dam, 3.5 to 8.5mm wide.	90,000	Canal De Isabel II, Madrid	Sealed under 90m of waterhead and high flow.
1980	Paradela Dam, River Cavado, Portugal	Concrete faced Rockfil 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 Hydro-electric Generation	470	146	Differential settlement of foundation rock due to power plant structure led to cracking of dam, encouraging further deterioration	50,000	Empresa Nacional Hydroelectric Del Ribargozana, Barcelona, Spain	Upstream layer of concret[e] grouted from vertical hol[es]
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 Hydro-electric 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	Koelnbrein Dam, River Malta, Kaernten, 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 concret[e] 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 rock + 6,500 in dam	TauernKraftwerke AG Salzburg, Austria	Resin used in rock grout test, and for dam fissure[s]
1986 -1987	San Esteban Dam, River Sil Orense, Spain	Concrete Gravity Dam for Hydro-electric Generation	295	116	Exploitation of vertical and horizontal construction joints promoting Alkali Aggregate Reaction.	100,000 (hor.) + 88,000 (vert.)	Iberduero SA, Bilbao, Spain	$5,300m^2$ in 22 joints treated. Also Upstream fa[ce] membrane applied.
1988 -1989	Karakaya Dam, River Furat Turkey	Double Curvature Arch Dam for Hydroelectric Generation	462	175	Differential compressibility of rock in abutments leading to massive tear fissure through the dam.	55,000	Devlet Su Isleri, Aukara, Turkey	Treatment of new dam.
1988	Dam "A" USA	Concrete Gravity Dam	320	65	Exploitation of vertical and horizontal construction joints leading to severe seepage volumes and uplift pressures.	7,200	N/A	First North American Application

Table 1. Summary details of major dam repair projects involving RODUR



SEEPAGE MONITORING POINT	ELEV. (FT.)
S-3	1658
S-4	1754
S-5	1736
S-6	1730
24-6	1723
S-7	1700
S-8	1688
6-5	1698

Figure 4. Plan and typical sections showing instrumentation locations and blocks to be grouted. (Dimensions in feet)

4.1.2. Details of Seepage Behavior

Annual maximum and minimum flows through the Left Abutment are summarized in Table 2.

Date of Maximum Flow	Maximum Flow (Liters/min)	Minimum Flow In Previous Winter (Liters/min)
Early Aug. 1984	2350	270
End July 1985	630	190
End July 1986	500	80
End July 1987	3630 +240 from new drain	190

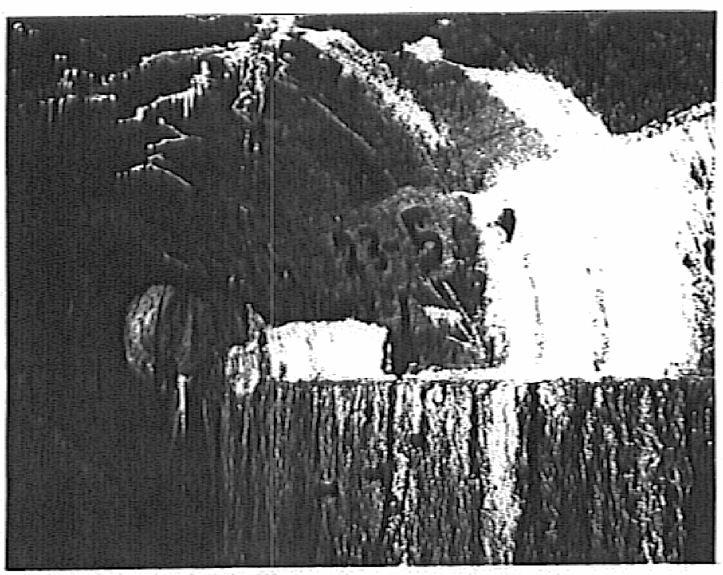
Table 2. Summary water flow data from Left Abutment (Point S-8, Figure 4)

The flow was recorded mainly below the Upper Gallery between Points S-6 (El 1730') and S-7 (El 1700') and was entering the Lower Gallery principally through the horizontal lift joints, and the large diameter (300mm) chimney drains linking the two Galleries (Photograph 1). The water chemically was very pure, and there was considerable deposits of calcite on both upstream and downstream sides of the Gallery. By 1987, there was also considerably more seepage from longitudinal secondary fissures in the roof, and from the downstream side of the Gallery than previously. (Photograph 2)

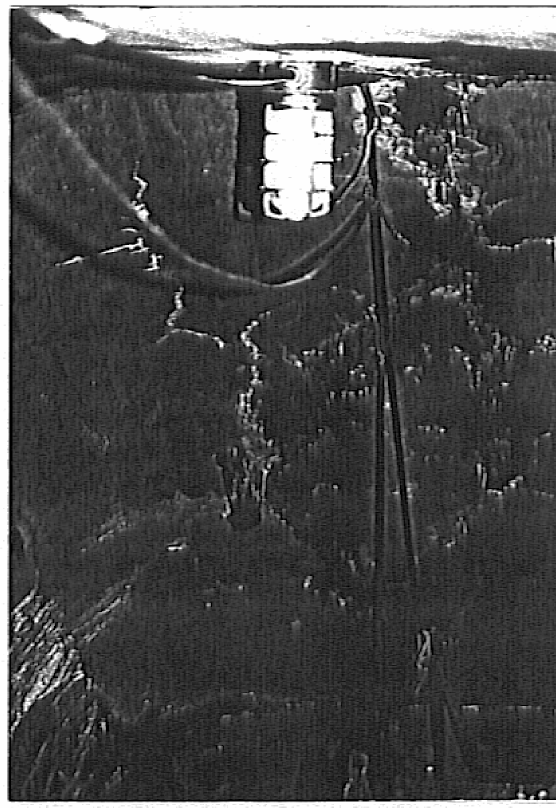
The Consultants concluded that the cyclic nature of the flow was most strongly influenced by reservoir head, and to a lesser extent by temperature variations. The latter, especially near the crest, would have the potential to reduce compressive forces on the upstream face, thereby allowing easier exploitation of existing construction and lift joints by higher lake levels.

The very pure lake water also had a high potential for solution which would gradually increase the fissure aperture and futher reduce the frictional characteristics of the joints (Photograph 3).

The seepage entering the downstream side of the Gallery indicated that hydrostatic pressures had developed which had not been fully controlled by the drains and galleries. The development of such pressures across the dam section would further reduce compressive stresses in the dam leading to increased seepage and concerns for decreased overall stability.



Photograph 1. Water inflow into Lower Gallery from large diameter chimney drain (left). Note also calcification on walls from seepage through horizontal joint.



Photograph 2. Water seepage from longitudinal secondary roof fissure in Lower Gallery.

4.1.3. Construction Characteristics Influencing Seepage Behavior

Conceivably the seepage could have been occurring through open joints and fissures, or through porous zones. The Consultants reviewed the original construction records, concentrating on those Left Abutment Blocks contributing most to the quantity and variability of flow (i.e. excluding Blocks 22, 26 and 27). Significant findings were as follows:

- Delays in Construction. The following significant breaks in construction were recorded between successive 1.5m concrete lifts:

Block	El	Period of Delay
21	1700'	Oct.' 26 - May' 27
23	1700'	April' 27 - Oct.' 27
24	1710'	Jan.' 27 - May' 27

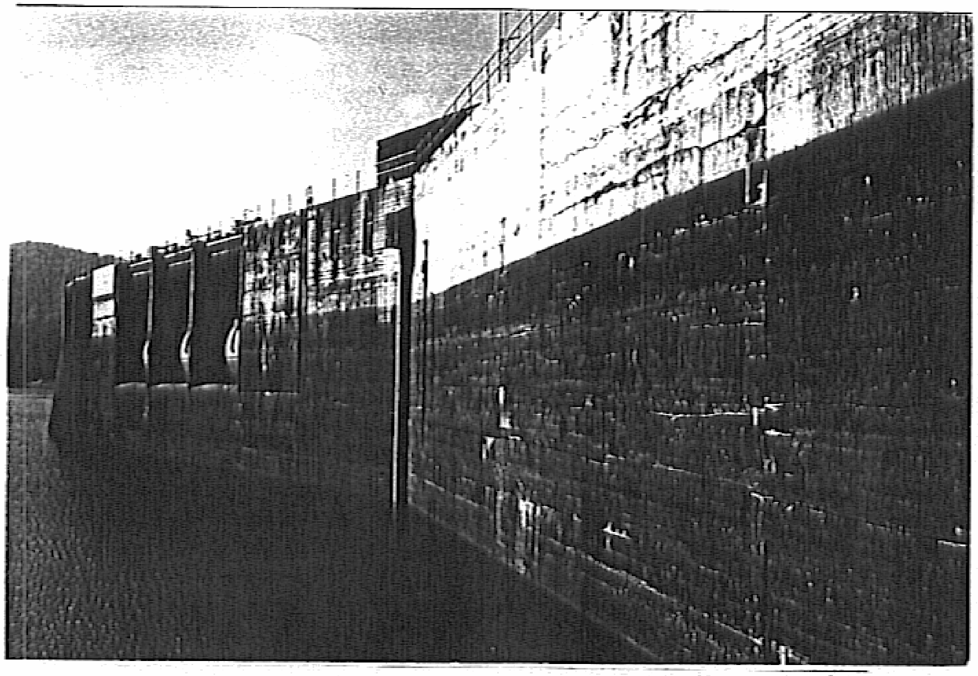
Such breaks can produce 'cold joints' reducing bond between lifts, subject the exposed surface to freeze-thaw cycles, and affect the lower concrete of the next lift.

- Composition of Concrete. After December 1926, the water/cement ratio of the concrete was greater than 1, and often as much as 1.1 to improve workability. Such high ratios lead to segregation, bleed, and low strength: phenomena most accentuated at construction joints. Typical 28 day strengths were 16-19N/mm^2.

- Construction Practices. Other practices which could later be aids to water transmission were identified:

-- very low temperature concrete placing leading to poorer quality concrete and inclusion of pockets of ice.

-- experimentation with admixtures to increase workability.



Photograph 3. Upstream face of dam showing clearly horizontal lift joints, and vertical construction joints between blocks.

-- placing dry cement on top of lifts to allow use of vibrators, but thereby generating a zone without proper consistency, and with a high susceptibility to attack by water.
-- "plumbstone" boulders, up to $5m^3$ in volume, were positioned by chains which were then excavated out, leaving the voids under the blocks to be backpacked by hand.
-- ponding of water, leading to a decrease in the strength and permeability of the upper concrete.

4.1.4. Remediation Measures

The Consultant concluded that measures be put in hand, directed towards certain horizontal construction joints, and intended to reduce the cyclic, increasing seepage behavior. The aims were to

- Reduce uplift due to seepage pressures within the dam.
- Reduce the rate of deterioration of the concrete along the seepage paths.
- Reduce monitoring and maintenance requirements associated with the seepage.
- Increase confidence in the integrity of the dam.

Following a consideration of various options, including anchors and face membranes, the prime methods recommended were the grouting of the lift joints, and the drilling of additional drainage holes from within the galleries. (Not described in this paper.)

The Consultants defined the blocks to be grouted and the two horizontal joints in each requiring special attention (Figure 5). Desirable grout properties were listed as:

- to ensure maximum penetration, the grout should be a true liquid and not a suspension of solids.
- the grout should be immiscible in water.
- the grout should have a short hardening time (to minimize washout).
- the grout should have a nearly constant viscosity until setting.
- the grout should not shrink after hardening.
- the material should have a low compressive modulus, but high sheer strength.
- the material must be durable.
- the material should be chemically stable and non toxic during preparation, and in service.

The grout was also required to be placed as close to the face as possible, and at full summer pool when the fissures would be most open. In this way no tension would later be applied to the grout/joint interface in the event of a significant structural movement later occurring at lower pool.

Bids were called in February 1988 on the basis of documents allowing the Contractor considerable scope in conforming with these general outline requirements.

4.2. CONCEPT OF TREATMENT

The authors' companies secured the contract on the basis of a Technical Proposal incorporating the following fundamental assumptions:

- Given that very little was known about the actual source of the flows, and their mode of occurrence (i.e. through horizontal joints, vertical joints, or pores), it was the declared intent to examine and treat only the two prescribed horizontal joints in each block.
- For the same reasons, this whole program of treatment was to be regarded as exploratory in nature.
- For reasons consistent with the proper application of the Rodur System, all drilling was to be conducted from the Lower Gallery with a small diameter core drilling system.
- Appropriate epoxy resin formulations were to be used to seal the joints.
- The work in each block would be conducted in a "step by step" way, to optimize the exploration of the structure and the verification of the treatment.

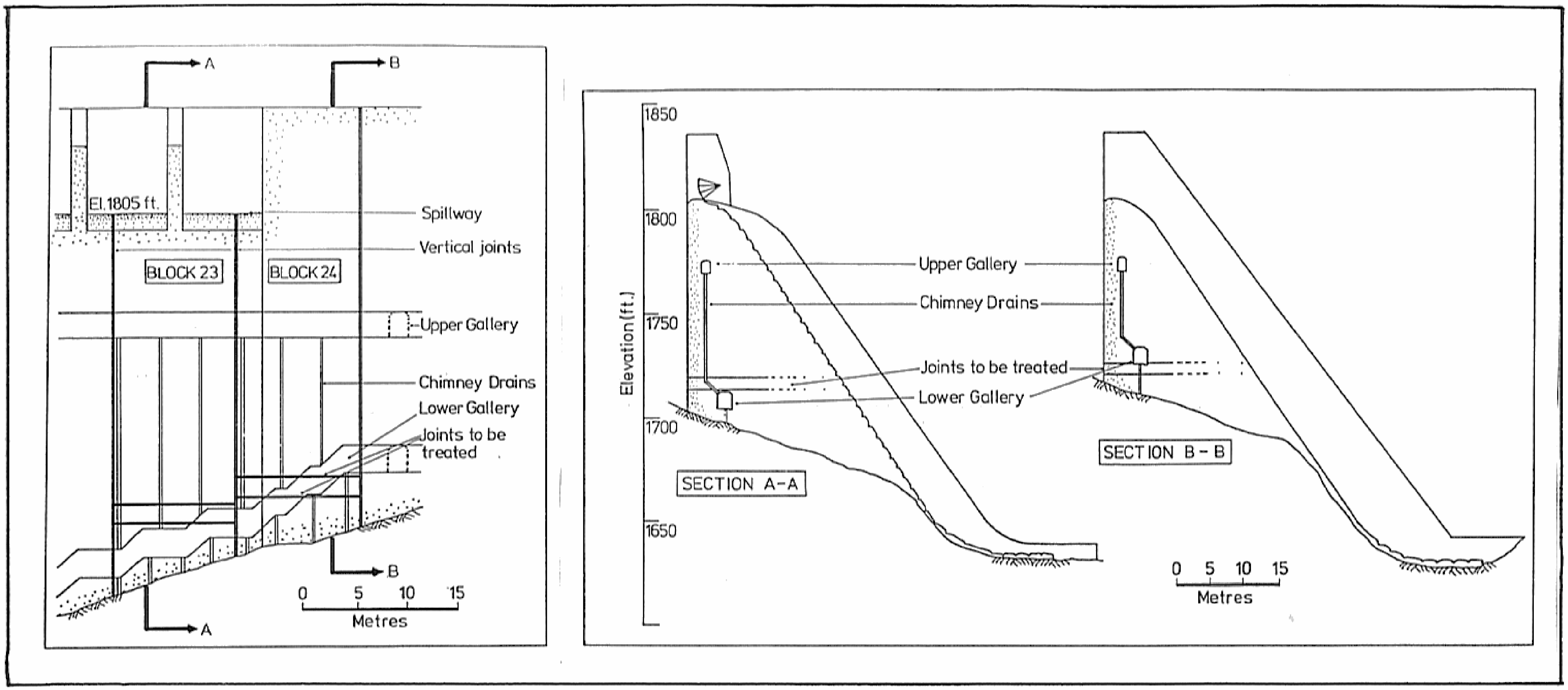


Figure 5. Horizontal joints investigated and treated in Blocks 23 and 24.

4.3. DESIGN OF PRIMARY GROUT HOLES

To obtain maximum information about the dam, the water flow patterns, the joints and the effectiveness of the grouting, every hole was cored full length. To improve directional control, and to economize drilling quantities, all grout holes were drilled from the Lower Gallery, approximately 2.1m wide and 2.5m high.

For each horizontal joint in each of the two blocks (23 and 24) being treated, holes were designed to intersect it at regular intervals (Figure 6). The two Primary rows were to be drilled and grouted before locating and drilling Secondary and later holes. As shown in Figure 5 the elevation of the Lower Gallery was not constant and so its position relative to the joints being drilled varied constantly. Therefore, to ensure the correct points of intersection of the joint, a scaled section had to be drawn for each hole location to calculate hole length, inclination and gallery wall entry point (Figure 7). At each station two holes were drilled--one into each joint--and these were oriented orthogonal to the Gallery wall and so the dam's face. Each hole was designed to terminate slightly beyond the target joint so that the concrete both above and below it could be studied.

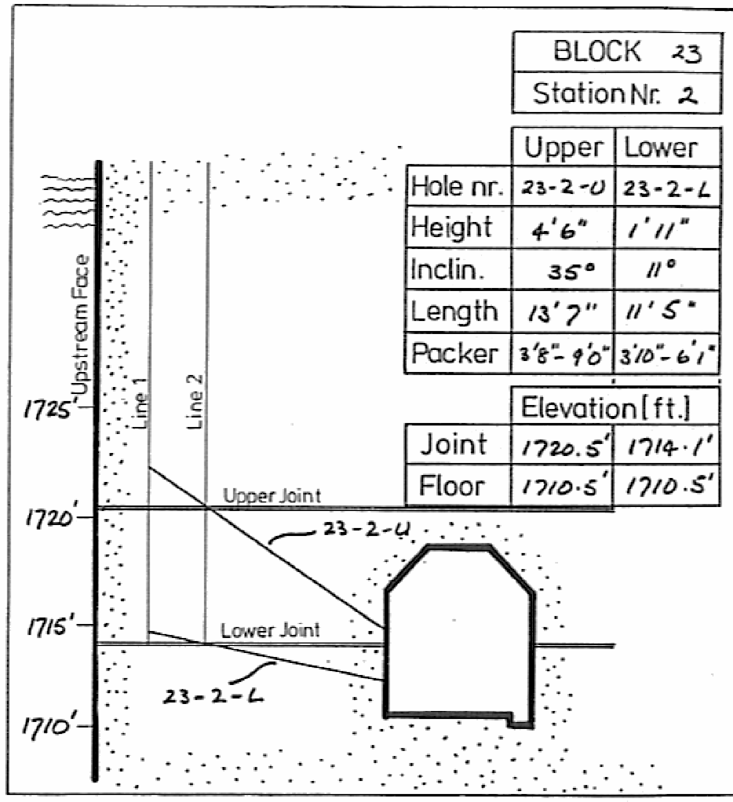


Figure 7. Typical section showing intended joint interceptions at one station.

4.4. EXECUTION

4.4.1. Drilling

A special modular frame mounted electrohydraulic rig was used (Photograph 4) to provide holes of 46mm diameter and cores of 36mm diameter. The length at which the joint was intercepted was carefully measured to give the real perforation pattern. Further analysis indicated the "roughness" of the joint as summarized in Table 3. The Secondary holes were located with respect to observations made during the Primary grouting. They were thus drilled into particularly "difficult" zones, or areas known to require close treatment (e.g. near large diameter drains or vertical construction joints. Each Tertiary hole was designed to penetrate both upper and lower joints about 1.5m and 3m back from the dam face respectively. Afterwards they were left open to act as seepage "tell tales" for the future. A summary of drilling quantities is given in Table 4.

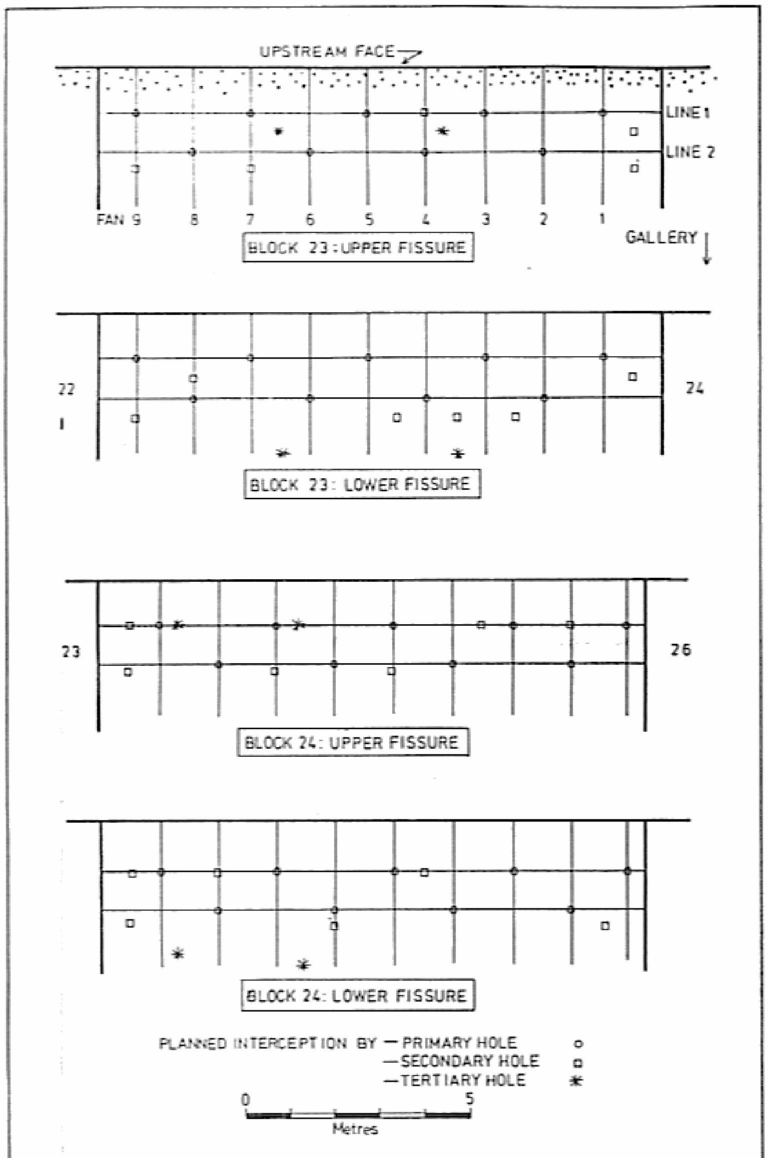
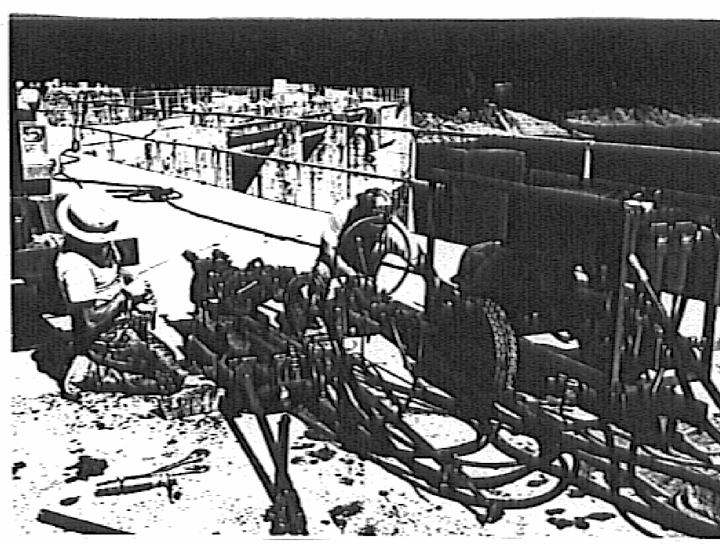


Figure 6. Plans of foreseen joint interception patterns.



Photograph 4. Components of the electrohydraulic coring rig. From left to right: mast with head, controls, power pack.

Horizontal Joint	Measured Elevation (Feet Above Sea Level)		
	From Primary Holes	From Secondary Holes	From Tertiary Holes
23 Upper Av. Range	1719.4 1718.8 to 1720.5	1719.1 1718.7 to 1719.4	1718.9 1718.8 to 1719.0
23 Lower Av. Range	1714.0 1713.3 to 1714.6	1713.9 1713.2 to 1714.2	1714.3 1714.2 to 1714.4
24 Upper Av. Range	1728.9 1728.5 to 1729.2	1728.9 1728.6 to 1729.6	1728.8 1728.7 to 1728.9
24 Lower Av. Range	1723.7 1723.0 to 1724.3	1723.8 1723.5 to 1724.1	1723.6 1723.5 to 1723.7

<u>Table 3</u> Summary of joint surface elevations, from grout hole data.

4.4.2 <u>Grouting</u>

After all the holes in one phase had been drilled they were fitted with mechanical packers terminating close to the joint. Consistent with the Consultant's wishes for the properties of the grout, the epoxy resin range was the only viable option. Its ability to not only seal the joints under extreme seepage conditions, but to bond the concrete surfaces together offered an attractive potential to structurally improve the dam. As the set resins typically have moduli of elasticity that are far lower than that of even poor concrete, this bonding action would not necessarily produce a structural "hard spot" in the dam. Thus while it would be hoped that movements in the vicinity of the grouted area would be reduced, the resin's elasticity would still allow it to withstand strains without losing adhesion and allowing the return of the seepage. The bonding effect would also enhance the seismic performance of the dam.

Due to the initial uncertainty regarding aperture width and extent, two resins were brought to site - RODUR 1 and RODUR 2. They differed only in their rheological properties in the liquid phase, the former being less viscous. Their chemical and mechanical properties were similar. Each comprised a two part preparation, in which "Components A and B" were thoroughly mixed, usually for 3-5 minutes, prior to injection. Some of the mechanical properties are shown in <u>Table 5</u>.

As described below, even the RODUR 2 proved too thin by itself to combat the extreme flow conditions encountered initially in the wide, open fissures intersected. As standard practice, talcum powder was added to the resin prior to injection to increase initial viscosity. At the concentrations used (generally less than 20% by weight) there was no significant influence on set grout properties. The average polymerization time decreased several minutes but this merely reflected the extra energy applied by the mixer and the resultant temperature increase in the fluid resin.

The grout was mixed in the supply tubs and transferred to special air powered delivery pumps. Depending on the rate of injection required, these pumps gave maximum output pressure ranges of 24 or 48 times the input air pressure.

Grouting parameters and injection sequences were broadly predetermined, but amended in response to

Order Drilled and Grouted	Block and Phase	Holes (Nr.)	Total Drilling (m)	Inclination
1	23 Primary	18	77	9-50° up
3	23 Secondary	11	42	10-56° up
5	23 Tertiary	2	9	40.5° up
2	24 Primary	18	71	39° down to 45 ° up
4	24 Secondary	12	46	48.5° down to 49° up
6	24 Tertiary	2	9	33.5-46° up
Total		63	254	

<u>Table 4</u> Hole drilling summary (Note: In addition two Drain Holes were drilled downstream, after grouting each block. All were dry.)

	RODUR 1	RODUR 2
Description	Liquid epoxy resin compound with amine hardener composition, free of solvents, two components.	Liquid epoxy resin compound with amine hardener composition, free of solvents, pigmented, two components. Component A: epoxy liquid resin, plus minerals and pigments Component B: based on a cyclo aliphatic amine
General	Free of solvents and mineral aggregates, its low viscosity allows use for very fine cracks, and in presence of water at low temperatures.	Hardened material has very low creep under compression. Liquid resin has excellent reistance to wash out by flowing water
Fluid Properties		
• Viscosity at 20° C (Brookfield Visc.)	2000/3000 MPa. S.	6500/7500 MPa.S
• Mean Surface Tension (liquid)	50 dyn/cm	50 dyn/cm
• Pot life	Approx. 50 min at 20° C	Approx. 90 min at 20° C
• Lowest hardening temp	4° C	4° C
• Water absorption of hard resin at 23° C	1.98%	1.8%
• Specific gravity at 20°: liquid	1.10 g/cm^3	1.93 g/cm^3
solid	1.19 g/cm^3	1.99 g/cm^3
Mechanical Properties (Values depending on Test Conditions)		
• Compressive Str.	95 Mpa	110 Mpa
• Flexural Str.	40 Mpa	35-40 MPa
• Tensile Str.	28 Mpa	20 Mpa
• Elong. at failure (Tensile)	3%	2%
Adhesion Tests (Cylindrical concrete specimens bonded with resin in different conditions, at 20°C. Simple tensile test.)		
• Dry Concrete	100% of samples break in concrete	100% of samples break in concrete
• Damp Concrete	80% of samples break in concrete	80% of samples break in concrete
• Submerged Concrete	65% of samples break in concrete	60% of samples break in concrete

Table 5. General properties of RODUR Series resins used in Dam "A".

observations on grout travel and pumping characteristics. Generally excellent resin communication was established between and beyond adjacent holes in the same joint, providing encouragement that a comprehensive treatment was being effected. In addition, there were resin connections

- with the large diameter chimney drains intersecting the fissures being grouted
- into vertical construction joints between blocks
- through vertical secondary fissures running between joints
- back into the Gallery where the joints were exposed (Photograph 5)
- from secondary longitudinal microfissures in the roof of the gallery

The Primary treatment and the Secondary grouting of especially troublesome zones were conducted with the viscous RODUR 2 grout, with talc. Late stage injection into smaller and tighter fissures and joints was conducted with the less viscous RODUR 1. Close examination of pumping rates (Table 6) and grout consumptions (Table 7) for the successive phases confirmed the "tightening up" of the joints: the pumps had to work several times harder in these

Photograph 5. Resin flowing back into Gallery through horizontal joints from points of injection 3m distant.

Block	Phase	Typical Pump Cycles/min	Typical Air pressure (N/mm^2)	Notes
23	Prim.	80-100	2	----
24	Prim.	50-90	2-3	----
23	Sec.	40-60	5-9	Pump exhaust icing up.
24	Sec.	40-50	7-9	Ditto

Table 6 Pumping characteristics (generalised)

Prim. - Primary Phase
Sec. - Secondary Phase

PHASE JOINT	PRIMARY			SECONDARY			OVERALL		
	Weight (kg)	Time (min)	Rate (kg/min)	Weight (kg)	Time (min)	Rate (kg/min)	Weight (kg)	Time (min)	Rate (kg/min)
23 Upper	713.3	89	8.0	508.3	104	4.9	1221.6	193	6.3
23 Lower	752.0	122	6.2	736.8	176	4.2	1488.8	298	5.0
23 Total	1465.3	211	6.9	1245.1	280	4.4	2710.4	491	5.5
24 Upper	1803.2	342	5.3	662.6	171	3.9	2465.8	513	4.8
24 Lower	1430.3	229	6.2	564.1	150	3.8	1994.4	379	5.3
24 Total	3233.5	571	5.7	1226.7	321	3.8	4460.2	892	5.0
Overall	4698.8	782	6.0	2471.8	601	4.1	7170.6	1383	5.2

Table 7 Weights of resin, and rates of injection per joint and phase.

Secondary holes, while the same holes took barely half the volume of the Primaries at slower injection rates.

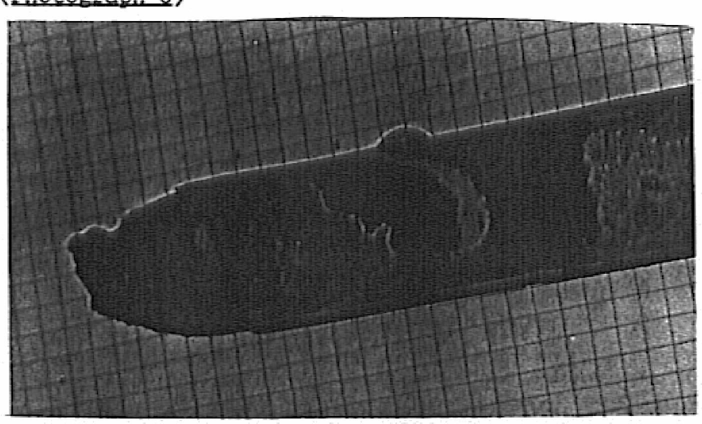
4.4.3. Fissure Observations

The visual characteristics of each joint intersection by a Primary hole were recorded. From an examination of these descriptions, basically five different joint types could be determined, as shown in Table 8.

Typically the material of the dam appeared to be of good quality. Soft or honeycombed concrete was restricted to the top 80mm of concrete pours although several smaller isolated and unconnected cases were recorded throughout, and expecially in Block 24. No major secondary fissures were encountered in the cores. Evidence of alkali-aggregate reaction was found in many samples but appeared to be of small scale and did not appear to have weakened, cracked or stressed the core samples in question. Old formwork timber, and steel grout pipes were also occasionally encountered. In one hole, a zone of washed concrete about 130mm thick was recorded just above the lower joint, but this extent and type of material weakness was exceptional.

Generally, and predictably, Category 1 and 2 joints carried the lowest rate of water flows whilst the higher water flows were common in all the other categories.

Plotting the evidence of resin recovery from the Secondary and Tertiary holes provided data on joint widths, as summarized in Table 9. In most of the Primary specimens the resin was poorly bonded to the usually dirty concrete surfaces. The resin either debonded during drilling or could be easily prised off during subsequent handling. However, all of the eight Tertiary hole samples showed good resin adhesion, especially in the five samples containg both Primary (thick) and Secondary (thinner) samples. (Photograph 6)



Photograph 6. Core from Tertiary hole showing resin bonding across the (oblique) joint. Note also resin penetration of seconday microfissure to left of main joint.

HORIZONTAL JOINT TYPE	23 Upper	23 Lower	24 Upper	24 Lower	Overall
1. Well defined hard surfaces, clean and tight	4	2	1	1	8
2. Well defined hard surfaces, slight coating of brown debris.	2	0	0	1	3
3. As 2, except for heavy debris, soft and easily moved.	1	5	3	3	12
4. Softer, less well defined, usually with moderate/heavy brown debris.	0	1	2	2	5
5. Lower side of joint has up to 80 mm of soft, milky concrete. Top side of joint hard.	2	1	3	2	8
Number of Intercepts	9	9	9	9	36

Table 8 Categorisation of horizontal lift joints cored in Primary drilling operations.

4.5. WATER FLOW OBSERVATIONS

The routine seepage measurements were maintained in the Left side of the dam during the works (Table 10). In addition, twice daily readings were taken of the flow from each borehole open at that time (Figure 8). Holes with particularly strong flows (over 200 liters/min) were fitted with packers and the pressure head noted. Typically this corresponded exactly to the theoretical hydrostatic pressure acting at the level of the fissure.

Primary holes were completely sealed off during Primary grouting. Similar flow records were maintained during the Secondary operations, supplemented by data from other flow sources such as the large diameter chimney drains, vertical roof drains, and fissures exposed in the Gallery. Again complete sealing of grout holes was recorded.

Joint	Summary Characteristics (Generalised)	Total Resin (kg)
23 Upper	Prim.3mm irregular Sec. 1-2mm irregular	713 508
23 Lower	Prim.1-6mm irregular Sec. 1-2mm regular	752 736
24 Upper	Prim.4-5mm regular Sec. 1-2mm regular	1803 663
24 Lower	Prim.4-10mm irregular Sec. 1-2mm regular	1430 564

Note Prim.- Primary grout thickness
Sec. - Secondary grout thickness

Table 9. Summary of resin thicknesses and weights.

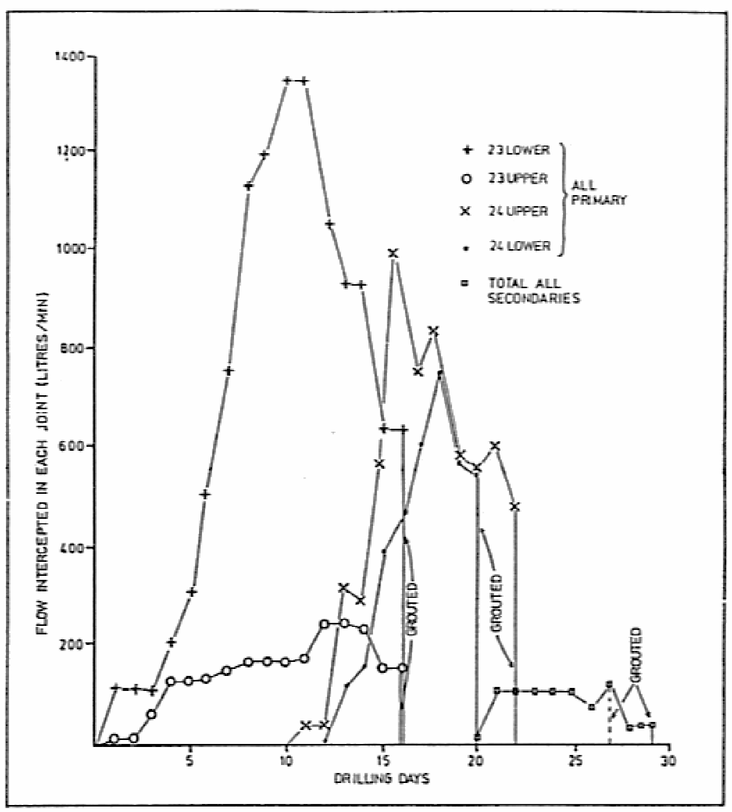


Figure 8. Water flows encountered by grout holes into each joint.

				MEASURED FLOW INTO BLOCKS 23/24							
Date	Lake El. (ft)	Cum. flow at S5	Cum. flow at S6	Joints etc. 23	Joints etc. 24	Grout Holes 23	Grout Holes 24	Total in 23+24	Cum. flow at S7	Cum. flow at S8	Total Left Abutment
8/1	1794.1	330	440	210 c	425	-	-	635	1075	1405	1575
8/8	1791.5	280	400	225 c	420	-	-	645	1045	1215	1385
8/15	1789.7	285	405	165 c	400	-	-	565	970	1235	1400
8/22	1787.7	265	395	155 c	345	-	-	500	895	1165	1310
8/29	1785.9	260	370	130 c	330	-	-	460	830	1075	1215
9/6	1786.2	245	330	140 c	310	-	-	450	780	1010	1140
9/12	1786.1	245	310	130 c	285	-	-	415	725 R	905	1030
9/19	1786.2	245	315	130 *	285 *	-	-	415	730 R	925	1040
9/26	1786.6	245	315	130 *	285 *	420	-	835	1150 C	1245 R	1360 *
10/3	1788.3	245	320	115 *	285 *	1320	-	1720	2040 C	2115 R	2190 *
10/10	1788.3	265	340	115 *	265 *	1125	430	1935	2275 C	2380 R	2455 *
10/17	1788.1	265	340	Incl.	160	20	1130	1310	1650 C	1775 R	1890 *
10/24	1787.8	265	340	Incl.	115	115	-	230	570	780 R	870
10/28	1787.6	245	315	Incl.	165	5	25	195	510	610	710
11/7	1789.1	210 *	265 *	Incl.	115	-	-	115	380 C	430	530

* Projected
c Calculated from Owner's data plus Contractor's readings.
R Revised from original data (certain readings at standard locations could not be made accurately or at all during the works)

Table 10. Measured water flow data in liters/minutes. (See Figure 4 for location of measuring point.)

Finally, records were maintained of the total seepage into the blocks after Secondary grouting. Water temperatures were also recorded to help locate the level in the lake at which the water was entering the structure. It is noteworthy that by far the greater part of the final flow into the grouted section (105 out of 115 liters) was recorded by a large diameter chimney drain in Block 24. By lowering an inspection lamp down from the Upper Gallery, the major source of the inflow was identified as being a horizontal joint at El 1739' - well above the level grouted in this program.

A further observation made during the Primary grouting was the cessation of several small seeps and leaks on the downstream side of the Gallery. The walls of the Gallery, on both sides, and hitherto completely saturated, began to dry out at this time.

4.6. OVERVIEW

The drilling system adopted proved ideal in accurately locating the targetted joints in a pattern generally very close to that anticipated. The system also proved capable of retrieving samples of resin injected in the Primary and Secndary grouting phases.

Departures from the intended pattern of hole intersections on any one joint were caused by the variability of the elevations of the original concrete surfaces when cast. This is summarised in Table 3 which shows that whereas the average figures were in close accordance in each phase, and in relation to the theoretical, the overall range in elevation across any one joint was 1.1' to 1.8' (330 to 533mm). This scale of variation could be observed on the joints exposed at the dam's upstream face. (Photograph 3)

The concrete itself was found to be in good condition with few examples of inferior quality away from the immediate elevations of the fissures. There were indications of alkali-aggregate reaction, but no sign of mass distress resulting.

The joints fell into five broad categories with the most common observation being of samples showing well defined surfaces, coated with dark brown sediment and organic material. Such holes invariably gave high water flows at pressures close to hydrostatic. Another common observation was to find a thin zone of soft concrete on the underside of the joint, and a hard, well-defined surface above. Such samples were mainly found further back from the face and were associated with both high and low water inflows.

Little evidence of major secondary fissuring was recorded in the zones drilled, although they were observed (and connected with resin) running longitudinally along the roof of the Gallery.

All the data confirm that the water was almost wholly flowing in the major horizontal lift joints recorded in each block, and not through any significant system of interconnecting pores or secondary fissures. The grouting data further confirmed direct connection up through the vertical construction joints, expecially the one between the two blocks. It was also observed that on the downstream side of the Gallery, the thickness of calcite deposits decreased progressively away from the vertical joints, further highlighting the role of the verticals in transmitting seepages downstream.

Regarding the grouting, the need to use talc was in response to the initially very open nature of the joints, and the very strong water flow characteristics through them. During grouting, the pattern of resin connections between grout holes, and into drains confirmed the desired travel of the grout. Similarly the drying up of seepages from old drain holes, and secondary fissures (on both walls and roof) pointed to comprehensive treatment.

The Secondary cores confirmed the large initial joint apertures and the fact that resin travel was quite uniform except at block extremities. This was rectified in the Secondary grouting.

Analysis of the grouting parameters - especially pumping characteristics and grout consumptions - demonstrated a marked "tightening up" in the Secondary injection phase, as is saught in classical grouting practice. This was further demonstrated by the final stopping of seepages remaining from the Primary grouting and the ability to inject the thin secondary fissures referred to above. Furthermore, the evidence from the Tertiary holes was especially reassuring: excellent bonding of the joints as a result of thinner Secondary grouts being forced into them at higher pressures following the "bulk infill" provided by the thicker Primary injections.

Period	Block 23	Block 24	Notes
Total flow before Prim. Drilling	130*	285	*Estimated
Total flow after Prim. Drilling	1320	1510	Average
Total flow after Prim. Grouting	20	160+	+From one drain (D9)
Total flow after Sec. Drilling	115*	210	*Mainly from one new hole
Total flow after Sec. Drilling	4	150+	+From same drain (D9)
Total flow after Sec. Grouting	4	115	Average

Table 11 Summary of water flows. (liters/minute)

After even the Primary grouting, the walls of the Gallery - previously saturated as a result of water seepage, probably for the whole life of the dam - began to dry out. This, together with the total seepage reduction (Table 11), is an eloquent statement of the effectiveness of the grouting in stopping seepage from the lake.

It is clear that Block 23 was almost completely sealed off, the remaining seepage (3 liters/min) aggregating from several trickles and drops from drains and pipes most likely penetrating sources above the levels injected.

In Block 24, less than 7 liters/min were continuing to enter at a fissure near the vertical construction joint, but below the elevations injected. Almost all the remaining flow (105 liters/min) was entering the Block through the large diameter chimney drain at the same station. Inspection and temperature measurements confirmed this flow as entering the drain through a horizontal fissure well above the zone grouted.

The performance of the dam, with respect to both movement and seepage is to be checked in the coming years to verify the longer term benefits of this program of resin grouting.

5. REMARKS

During the last decade, the Rodur process has been used with conspicuous success on many high concrete dams throughout the world. Its success is due as much to the meticulous way in which each dam's problem has been studied and understood, as it is to the extraordinary properties of the family of synthetic resins which have been developed as the grouting medium. The RODUR process is essentially a remedial tool. However, the case histories show that it can be utilized at any stage of a dam's life, from first impounding through sudden events (such as at Zeuzier Dam) to a final solution for long standing deteriorating situations. With dam repair by grouting, there is typically only one chance: an abortive attempt with inappropriate materials can seriously reduce the potential effectiveness of any later program. This realization has often been a key factor in the decision to use the RODUR method.

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