Use of cement based grouts in the rehabilitation of concrete dams: a review

João Ricardo MARQUES CONDE DA SILVA [1]

[1] National Laboratory for Civil Engineering, Lisbon, Portugal

Contact e-mail: jrsilva@lnec.pt

ABSTRACT: Cement based grouts are commonly used for injections in concrete dams as part of rehabilitation operations of cracked dam bodies and degraded contraction joints.

This document addresses aspects such as assessment of the dam's stability, preparatory works, recommended practices, common methodologies and standard precautions concerning the injection of cement based materials for repairing cracks and contraction joints in these massive structures.

The main features related to the injection itself, including references to grouting materials, equipment and pressures and are also briefly discussed. Subsequently, a list of successful rehabilitation operation case histories is provided, including a short description regarding the anomalies and their causes as well as the rehabilitation methodology adopted for each situation.

1 INTRODUCTION

Grouting is the most common procedure for repairing and reinforcing cracked concrete dams, including the resolution of seepages. Grouting is used to both interrupt the deterioration process, e.g. by preventing water penetration through it, and, if possible, increase the structural safety level of the dam (Javanmardi and Léger, 2005).

It must always be borne in mind that filling cracks by grouting does not prevent the cause of cracking by itself. This repair method may (or, in many cases, should) be used in combination with other types of repair or reinforcement strategies that eliminate or mitigate the cause(s) of cracking, always taking into account the structural aspects of the cracks and ensuring greater longevity for the rehabilitation (Panasyuk et al., 2014).

The cement based materials have been successfully used for the injection of cracks and contraction joints in concrete dams, although other type of materials, such as epoxy resins and polyurethanes are sometimes considered as more adequate for these purposes. The current document aims at compiling some of the most relevant information concerning the use cement based grouts in the above mentioned contexts.

2 GROUTING OF CRACKS

ICOLD (1997) proposed the following general procedure for crack filling operations in concrete dams: eliminate the causes of cracking, re-establish design conditions, remove deteriorated concrete and, ultimately, protect and waterproof critical areas.

The repair methodology as well as the actual need for repair should be thoroughly planned, including economic viability and technical assessment. Alternative repair methodologies should also be considered based on the origin of cracking. For example, investigate whether the repair should be treated as cracking or as spalling. In case of concrete mass loss (such as cracking due to embedded metal corrosion or freeze/thawing action), replacement of deteriorated concrete, rather than grouting, is usually the best solution. There are some cases in which the conclusion is that nothing should be done in terms of repair or rehabilitation, such as in non-structural inactive cracks, which in turn may eventually be autogenously repaired (Delatte, 2009; Panasyuk et al., 2014).

When repair is required, it is necessary to define whether the purpose is solely to prevent water from passing through the crack(s) or also to reinforce the cracked area. The cracking in the upstream face must be sealed in order to improve the watertightness, which reduces seepage and avoids uplift development. Therefore, an elastic-plastic material that works as a water-stop should be injected, allowing relatively small displacements or, if the cracks cover a significant area of the upstream face, it may be appropriate to fully waterproof the upstream face, e.g. with a membrane. This type of solutions is effective in eliminating infiltrations and in the protection of concrete against aggressive waters, in order to prevent its degradation (ICOLD, 1997; Woodson, 2009; Harrison, 2013).

On the other hand, if it is also intended to restore some of the structural continuity or if cracking is considered to compromise the overall stability of the dam, a structural analysis should be carried out before, during and after the repair operation (ICOLD, 1997; Javanmardi and Léger, 2005), which can be supported by numerical models. Below (2.1 Structural aspects), some considerations about the use of this type of procedure are presented.

The season of the year at which the injection takes place is another important aspect, since the success of the works depends, among others, on the temperatures of the concrete, of the air and of the surrounding water. The humidity conditions to which the crack is exposed and the reservoir level are also determining the success or fiasco of an injection. Generally speaking, the filling of cracks in concrete dams should start at the upstream face, from the bottom proceeding upwards, before the application of a waterproofing membrane (if necessary) (ICOLD, 1997; Woodson, 2009; Corns et al., 1988; Panasyuk et al., 2014; Khayat, 1997).

2.1 Structural aspects

Cracks should only be treated after understanding their structural aspects. Ideally, any analysis of state and behaviour should focus on the whole system, i.e. dam-foundation-reservoir system, rather than just the dam body. It is important to understand the origin and the stress field at the deepest point of the crack, so that it can be repaired more effectively. Since the exact tensile field is very difficult to evaluate, it is advisable to use grouting techniques that maximize the structural strength of the treated crack (Javanmardi and Léger, 2005; Delatte, 2009; ICOLD, 1997; Corns et al., 1988).

A rigorous structural safety analysis of an injection operation should take into account the structural response of the dam during and after the injection, as well as its initial state, according to the illustration shown in Figures 1 and 2. These analyses might be undertaken based on numerical models such as finite element models, which introduce the geometry (location, length, depth and aperture) as well as roughness of the cracks, in order to analyse the cracked structure. The concentration of stresses in some areas should also be analysed. Discrete element models are also very helpful for such analyses. The cracked concrete dam should be analysed before the injection operation, in order to understand the cracked state and possible causes of cracking, as represented in Figure 1 (Javanmardi and Léger, 2005; ICOLD, 1997).

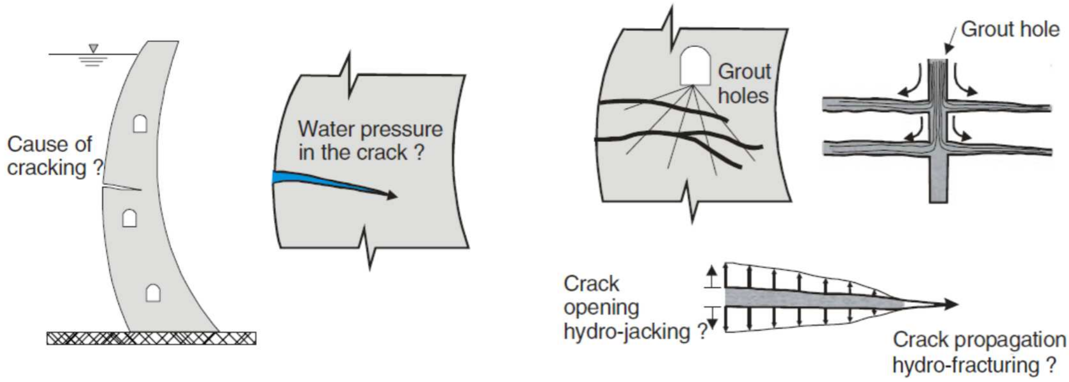

Figure 1. Structural response of dam before and during the grouting process: cracked dam, before injection (left); injecting grout in cracks (right) (adapted from Javanmardi and Léger, 2005)

The structural behaviour of the dam should also be estimated during the injection operation (Figure 1), due to the fact that the grouting process can introduce additional stresses in the structure, as a high injection pressure can increase the risk of crack opening (hydro-jacking) and crack propagation (hydro-fracturing). Hence, a low injection pressure is often recommended for grouting of cracks in unconfined concrete. Under static conditions the pressure at any point is determined from the density of the fluid, its vertical distance from the surface and the pressure at which it is injected at the surface. To these, friction losses should be subtracted (ICOLD, 1997; Javanmardi and Léger, 2005).

The stability should also be analysed during the change of state of the injection material (from liquid to solid). Finally, an examination of the dam's response to the loads after repair (with the injection material, after hardening) should also be undertaken, namely by assessing the potential for crack propagation due to both extreme loading and wedge effect (Figure 2) (Javanmardi and Léger, 2005; Khayat et al., 1997).

The grouting of a crack can be very effective for some load scenarios, but unfavourable for others. For example, grouting operations carried out during periods with high reservoir levels may be detrimental to the dam structure during a possible future reservoir emptying, and an identical effect can occur with pre-installed stresses due to grouting, if the seasonal thermal cycles are not taken into account (Corns et al., 1988). A grouting operation should be carried out with the empty reservoir and during the season at which the cracks are at their greatest aperture, i.e. the cold season. However, in some situations, in which the reservoir cannot be drained, an intervention with the unemptied reservoir might be the only repair solution (Javanmardi and Léger, 2005; ICOLD, 1997).

When one is faced with a crack system and not just a single crack, it is important to avoid cracks joining in one. In these cases, one of the priorities is to inject the crack tips closest to neighbouring cracks. In any case, a good adhesion to the crack walls should always be ensured, with special emphasis on critical zones such as the edges and ends of the cracks. Special care should also be taken with cracks forming contraction joints, as these should remain free to deform, and to the blockage of drain or pressure relief cavities, which must be avoided (ICOLD, 1997; Corns et al., 1988; Panasyuk et al., 2014).

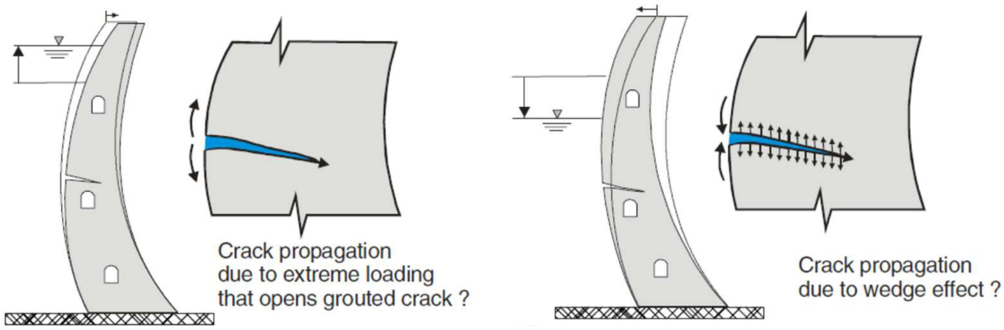

Figure 2. Crack propagation in the dam after the grouting process as a result of: extreme loading (left); wedge effect (right) (adapted from Javanmardi and Léger, 2005)

2.2 *Preliminary works*

The works preceding a crack injection job usually include the removal of the surface and interior layers of brittle concrete as well as cleaning and drying the intervention and surrounding areas. In addition to these, preparatory works for grouting the cracks include the drilling of narrow cavities crossing the cracks, especially in the presence of internal or very deep cracks, so as to intersect them and introduce the injection material through these new openings, the so-called grout holes (Figure 1). The diameter of the grout holes is commonly between 38 and 75 mm (Corns et al., 1988; ICOLD, 1997; Woodson, 2009; Panasyuk et al., 2014).

This type of perforations can be performed by rotary or percussion means. Drilling with rotary diamond drill bits should be accompanied by water injection which has the role of removing fine particles which, if not removed prior to injection, could block small cracks. Air-percussion drilling is cheaper than rotary drilling and is preferable if core sample recovery is not required. This type of drilling can also be accompanied by water injection to clear and clean the cracks. In this case, (ICOLD bulletin 107, 1997).

The injection preparation methodology also includes cleaning the concrete along the surface cracks and installation of vent ports with injection nozzles (grout nipples) along the crack to ensure a good connection between the crack and the injection device, which should fit into drilled holes to an approximate depth of around 50 mm. These vent ports should also be installed at crack intersections and the spacing between them should be shorter for finer than for larger cracks (e.g. 75 mm for up to 3 mm in width and 200 mm for larger cracks). The areas between each injection port should then be sealed with a cement paint, sealant, or grout (e.g. fast setting two-component epoxy resin grout) (Khayat, 1997; ICOLD bulletin 107, 1997; Woodson, 2009; Panasyuk et al., 2014).

The bond of the grout to the face of the cracked concrete depends on the cleanness of the crack. Infiltrated sediments or deposited reaction products can impair bond. So, the next step is to internally wash the crack with water blasting (pressures of around 25 MPa have been successfully used), which in turn also serves to test the sealing tightness. The existence of cavities that intersect the cracking system may also be advantageous in preventing the propagation of uplifts. In case of leakage, cracks should be resealed and retested. Pressure pointing (manually) may be required before grouting to prevent the grout escaping through joints or other cracks (Panasyuk et al., 2014; Javanmardi and Léger, 2005; Harrison, 2013; Woodson, 2009; Corns et al., 1988; ICOLD bulletin 107, 1997; Khayat et al., 1997).

3 REHABILITATION OF JOINTS

Contraction joints are grouted after completion of the construction in a cold season and sometimes re-grouted during the operation phase and, when necessary, re-grouted again as part of a rehabilitation process (PCOLD, 1985; Gouvenot et al., 1991; ICOLD, 2000). The main purpose of the rehabilitation of contraction joints is to restore their water tightness and, in some cases, bond and shear strength as well. As with injection of cracks, grouting of these joints is one of the main techniques currently used for repairing them. From the dam face or from the face of the gallery, an array of grout holes is drilled crossing the joint through which an appropriate sealant is grouted (Figure 3). Among other materials, normal and fine grade cement grouts have been used with success (Schrader, 1980; Gouvenot, 1991; Brighton and Lampa, 1991; Diaz, 1994; ICOLD, 2000; Noret and Laliche, 2017).

Sometimes the zone to be treated has to be confined before grouting starts. Special sealing devices must be used where important movements are to be accommodated by a joint. Typical in this category are those between aprons and the dam heel, or peripheral joints between the arches and the pulvino. Filling with slightly damp cement mortar, rammed into the joint to a depth of twice the width has been reported (Demmer et al., 1985; ICOLD, 2000).

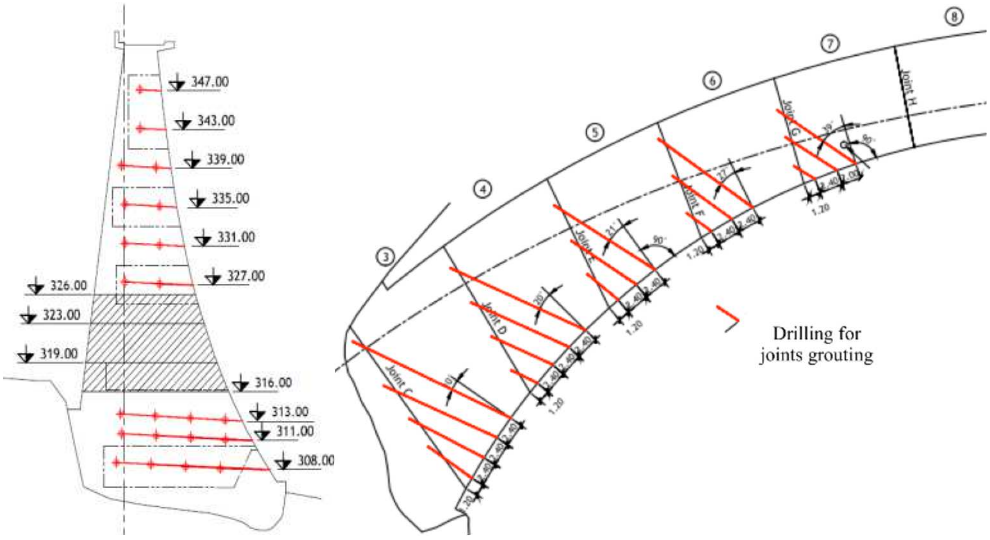

Figure 3. Illustration of the grout holes drilled for construction joints grouting: vertical section of cantilever (left); horizontal section of arch (right) (adapted from Noret and Laliche, 2017)

4 INJECTION PRACTICES

Modern injection techniques were fundamentally developed from practice, based on the experience of specialised personnel and empirical correlations (Javanmardi and Léger, 2005). The injection methodologies are essentially distinguished according to the types of repair and materials. Injection of cement or polymer-cement based grouts should be carried out under low pressure due to the presence of abrasive mineral particles, as opposed to what happens with the application of polymeric materials. This is the reason why the injection/application of cementitious materials is usually done with the same equipment usually used for the application of mortars such as membrane, screw or piston pumps (Figure 4), although for smaller volume applications with manual injection guns may be used (Panasyuk et al., 2014; Harrison, 2013). The specifications of the equipment must also be considered when defining the maximum pressures, productivity and maximum particle size of the cement particles and mineral additions (Table 1) (Panasyuk et al., 2014).

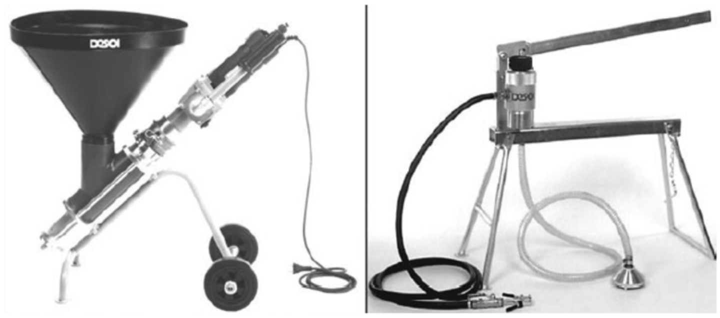

Figure 4. Screw pump SP-Y (left) and piston pump HP-60ZD (right) designed for cement and cement/polymer based materials (Panasyuk et al., 2014)

Unlike operations with other type of materials in which high pressures are used, the injection pressure is not a critical factor when it comes to injecting cementitious grouts since they are typically introduced into cracks under relatively low pressures through ordinary mortar equipment. The equipment for applying aqueous mortars in cracks normally allows the use of insoluble fillers with particle sizes between 0.3 and 3.0 mm. After filling each crack system, the injection pressure should be maintained for several minutes in order to ensure good penetration (Panasyuk et al., 2014; Javanmardi and Léger, 2005; Harrison, 2013; Woodson, 2009; Corns et al., 1988; Khayat, 1997).

After the grouting operation, the junction zone between concrete, repair material and concrete debris remains the most vulnerable zone due to different phenomena: mechanical (static or cyclical loads), chemical (aqueous solution, aggressive agents, minerals), biological (microorganisms) and physical (temperature variations, wetting-drying cycles, etc.) actions. It is not uncommon that the areas repaired by injection of cementitious grouts crack again, because of the relatively poor bond between the repair material and the repaired structure, as well as due to the relatively low strength of the repair material and to the temperature variations (Panasyuk et al., 2014).

Table 1. Specifications of screw pump (SP-Y), piston pump (HP-60ZD) and diaphragm pump designed for cement based injection materials (Panasyuk *et al.*, 2014; Khayat *et al.* 1997)

Parameter	Screw pump	Piston pump	Diaphragm pump
Power (W)	1800	N/A	N/A
Maximum working pressure (MPa)	1.5	2.0	0.7
Productivity (l/min)	1.5 to 13.5	150 ml (per stroke)	>0.9
Highest permissible grain size (mm)	3	0.3	N/A
Filling height (mm)	850	N/A	N/A

N/A - Information not available

5 CASE HISTORIES

A summary of successful case histories of the use of cement based grouts for dam rehabilitation purposes is presented in Table 2, including information regarding the type and causes of degradation, the grouting material, the injection pressure as well as some rehabilitation remarks.

Table 2. Summary of successful case histories concerning injection of concrete dams with cement grouts

Dam name and type	Year of completion	Hgt. (m)	Location	Type / Cause of degradation	Grouting material	Injection pressure	Rehabilitation remarks	Reference
Isle-Maligne, gravity dam	1926	43	Québec, Canada	Construction joints deterioration	Microfine cement grout	0 to 5 MPa	There was crack hydrojacking during injection	Turcotte et al. (1994)
Kuromata, gravity dam	1927	25	Japan	Leakage at the downstream surface of dam	Cement with hardening accelerator	0.3 to 0.7 MPa	Grouting has prevented further deterioration of the dam	Tada and Shibata (1991)
Big Eddy, buttress dam	1929	44	Ontario, Canada	Horizontal construction joints deterioration and leaching	Cement grout	Effective pressure + 0.7 kPa	Successful grouting with some minor seepage	Gore and Bickley (1998)
Pracana, buttress dam	1952	65	Portugal	Degradation at dam faces and cracks due to swelling react.	Cement grout and epoxy resin	N/A	Rehabilitation using geomembrane and grouting of cracks	Liberal et al. (2003)
Bimont, arch dam	1952	87	France	Cracking and degraded joints due to swelling react.	Cement grout	cracks: 0.1 MPa & joints: 0.4 MPa	Grouting of cracks and of contraction joints	Noret and Laliche (2017)
Storfinnforsen, buttress dam	1954	40	Sweden	Leakage and soaking of lime and cracking	Cement grout	N/A	Grouting of the cracks downstream and shotcrete of upstream face	Eriksson et al. (1994)
Daniel-Johnson, arch-buttress dam	1970	214	Québec, Canada	Cracking due to geometry of structure and thermal stress	Microfine cement w/ superplas-ticizer	1.15 to 2 MPa	Grouting of cracks resulting in no water seepage	Saleh et al. (2002)

N/A - Information not available

6 CONCLUDING REMARKS

The use of cement based grouts has been successfully used for both grouting of cracks in concrete dams and rehabilitation of contraction joints.
When faced with a cracked concrete dam, a structural analysis is recommended before any repair intervention, in order to understand the origin of cracking and to assess the stability of the dam and the impact of the repair operation on the structural behaviour of the dam.
The preparatory works for the grouting of cracks include drilling holes through which the grout is then injected, installing vent ports and injection nozzles along the surface cracks, sealing the external cracks as well as clearing and cleaning the internal cracks by water blasting.
As for degraded contraction joints in concrete dams, preliminary works also include drilling of injection channels to intersect the inner part of the contraction joints.
Concerning the injection itself, special care should be given to the choice of grouting material, injection pressure and equipment. Several other aspects should be taken into consideration before any of these grouting operations, such as the season of the year and the reservoir level at which the injection takes place.

7 REFERENCES

Brighton, R., and J. Lampa, 1991, Ageing of British Columbia Hydro's dams, *17th ICOLD Congress*, Vienna, Q65, R30.

CFGB, 1976, Infiltrations in hydroelectric dams in France, remarks, interpretation and treatment (in French). *12th ICOLD Congress*, Q45, R20.

Corns, CF, Jansen, RB and Lombardi, G. 1988. *Advanced dam engineering for design, construction and rehabilitation, 1st Edition*. Van Nostrand Reinhold Company.

Delatte, N. 2009, *Failure, distress and repair of concrete structures, 1st Edition*. CRC Press.

Demmer, W., and H. Ludescher, 1985, Measures taken to reduce uplift and seepage at Kolnbrein dam, *15th ICOLD Congress*, Lausanne, Q58, R81.

Diaz-Caneja Rodriguez, JI, 1994, Evaluation and increase of safety for dams in service in the basin of the Douro River. Remedial works, *19th ICOLD Congress*, Durban, Q68, R30.

Eriksson H., 1994, Investigation and rehabilitation of the Storfinnforsen dam, *18th ICOLD Congress*, Durban, Q68, R19.

Gore IW, and Bickley JA, 1998, Investigation rehabilitation of a severely deteriorated concrete gravity structure: Big Eddy Dam. *ACI Concrete International*, 9(6), 32-38.

Gouvenot, D., B. Bouyge, J. Francq, A. Jensen and M. Meyerfeld, 1991, Loss in sealing due to aging of the dam bodies. Practices in developing corrective actions (in French). *17th ICOLD Congress*, Vienna, Q65, R40.

Harrison, DM, 2013. *The Grouting Handbook - A Step-by-Step Guide for Foundation Design and Machinery Installation, 2nd Edition*. Elsevier, Inc.

ICOLD, 1997 - *Control and Treatment of Cracks – Review and case histories*, bulletin 107.

ICOLD, 2000 - *Rehabilitation of dams and appurtenant works – State of the art and case histories*, bulletin 119.

Javanmardi F., and Léger P., 2005, Grouting of cracks in concrete dams: numerical modelling and structural behaviour, *Progress in Structural Engineering and Materials*, 7, 161-173.

Khayat, KH, G. Ballivy, and M. Gaudreault, 1997, High-performance cement grout for underwater crack injection, *Canadian Journal of Civil Engineering*, 24, 405-418.

Liberal, O., D. Silva Matos, A. Camelo, A. Soares de Pinho, A. Tavares de Castro, and J. Machado Vale, 2003, Observed behaviour and deterioration assessment of Pracana dam. *21st ICOLD Congress*, Montréal, Q12, R12.

Noret, C., and Laliche, K. 2017. Bimont Dam Case - Studies and Investigations Inside the Dam Body, *Swelling Concrete in Dams and Hydraulic Structures, 1st Edition*, DSC2017, Wiley, ISTE.

Panasyuk, VV, Marukha VI, and Sylovanyuk, VP. 2014. *Injection Technologies for Repair of Damaged Concrete Structures, 1st Edition*, Springer.

PCOLD, 1985, Work group of the Portuguese Committee on Large Dams, Cracking and repair works at Cabril dam. *15th ICOLD Congress*, Lausanne, Q57, R21.

Saleh K., S. Tremblay, M. Lizotte, R. Lariviére, V. Roy and L. Routhier, 2002, Crack repair in concrete dams: identifying effective methods and materials. *Hydro Review*, 21(5), 40-49.

Schoberl, P., Duber, H., and Dopper, H. 1993. Force-locking crack injection at Zillergrundl Arch Dam (in German). *Grouting in rock and concrete*. Rotterdam: Balkema.

Schrader EK, 1980, Repair of waterstop failures. *ASCE Journal of the Energy Division*, 106, 155-163.

Tada S. and K. Shibata, 1991, Kuromata dam. Leakage prevention work. *17th ICOLD Congress*, Vienna, Q65 R58.

Turcotte L., B. Savard, G. Lombardi and H. Jobin, 1994, The use of stable grout and GIN technique in grouting for dam rehabilitation. *Canadian Dam Safety Association (CDSA) Conference*, Winnipeg, Manitoba, Canada, BiTech Publishers, 137-162.

Woodson, RD. 2009. *Concrete Structures: Protection, Repair and Rehabilitation*. Butterworth-Heinemann.