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MULTI-STAGE CHEMICAL TREATMENT OF CATACLASTIC-MYLONITIC ROCK TO REDUCE SEEPAGE UNDER AN ARCH-GRAVITY DAM (**)

SUMMARY

The seepage flow under Place Moulin Dam (near Aosta, Italy) was still remarkable (of the order of 10 liters per second) after intensive extra-fine cement grouting of fractured and laminated rock with interbeds of cataclastic and mylonitic materials. On the basis of laboratory and large scale tests, a multi-stage treatment has been carried out with different types of chemical mixtures: sodium silicate solutions with inorganic and organic reagents, phenolic resin solutions. The downstream seepage was substantially reduced and remained lower than 0,5 l/s during the subsequent impoundings of the reservoir.

RIASSUNTO

L'alta valle del Buthier, un affluente della Dora Riparia nei pressi di Aosta, fu sbarrata a Place Moulin con una struttura di calcestruzzo ad arco-gravità formante un serbatoio della capacità di 105 milioni di metri cubi.

Dopo il completamento della diga, nonostante il trattamento intensivo di iniezioni con sospensioni di cemento superventilato, eseguito negli anni dal 1963 al 1965, le filtrazioni residue erano ancora notevoli, dell'ordine di 10 litri/sec.

Si decise perciò, per ottenere una adeguata impermeabilizzazione e consolidamento dei materiali cataclastici-milonitici sottostanti la fondazione della diga, di intervenire con un ulteriore trattamento di iniezioni chimiche " *a più fasi* ", *ossia iniettando successivamente due o più tipi di miscela con penetrabilità crescente.*

Dopo accurate prove di laboratorio per la scelta delle miscele più adatte, e prove di controllo su larga scala in situ, furono adottati i seguenti tipi di miscele chimiche:

- *soluzione colloidale di silicato di sodio diluito con reagente inorganico (alluminato di sodio)*

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- *soluzione colloidale di silicato di sodio diluito con reagente organico (acetato di etile)*
- *soluzione pura di resina fenolica (resorcina formaldeide)*

Il trattamento fu eseguito per mezzo di parecchie file di fori ad interasse di 2 metri, a diversa inclinazione (da 0 al 25%) e profondità (30 ÷ 80 m), penetranti nella roccia da due gallerie a valle e a monte.

Il trattamento si protrasse per tutto il 1966. Durante i cicli di invaso e svaso del serbatoio furono sistematicamente registrati i flussi di filtrazione. La portata filtrante diminuì fino a registrare, alla fine del 1966, un flusso di circa 0,5 l/s, venti volte inferiore a quello misurato l'anno precedente sotto lo stesso carico idraulico. Ciò conferma pienamente l'efficacia del trattamento chimico a più fasi.

1. INTRODUCTION

1. 1. General

The recent development of grouting procedures permits the treatment of any type of soil (with the obvious exception of fine silts and clays) and fissured or porous rocks, where a higher strength and or a lower permeability are required.

With reference to their rheological properties the most known mixtures can be classified as follows:

a) suspensions of solid particles in water (cement, clay or bentonite, fillers, etc.)

b) colloidal solutions (sodium silicate with inorganic or organic reagents, ligno-chromates, bituminous emulsions, etc.)

c) pure solutions of monomers (phenolic, acrylic and amino resins).

All the suspensions (Binghamian fluids) have an initial rigidity or cohesion, thus requiring a certain pressure to start the flow.

Both cohesion and viscosity increase with time; moreover the penetrability may be reduced by loss of water due to sedimentation and drainage.

The colloidal solutions are « evolutive » Newtonian fluids, i.e. without cohesion but still with a gradually increasing viscosity. When high final strength is not required, adequate selection of chemicals and dilution enable a rather constant penetrability within a considerable fraction of the setting time.

The pure solutions are « non evolutive » Newtonian fluids, i.e. they have no cohesion and a constant viscosity until setting. These properties, associated with a very low viscosity, allow the impregnation of the finest grained or fissured media up to the practical and economic limits imposed by the rate of flow and pressure (to avoid the uncontrolled rupturing of the soil).

Within each rheological class, a wide range of strength can be obtained but the cost, depending mainly on penetrability, increases to a great extent passing from suspensions to pure solutions.

In non-homogeneous media (and therefore in most practical cases) the best results can be reached by injecting in succession two or more grouts with increasing penetrability in order to minimise the quantities of the most expensive products which are required to complete the treatment.

A successful application of the multi-stage technique was made after the completion of Place Moulin Dam to reduce residual seepage.

1. 2. Main features of the dam site

The upper valley of the Buthier, a tributary of Dora Riparia River (near Aosta, Italy) has been dammed at Place Moulin by an arch-gravity concrete structure creating a reservoir with a storage capacity of 105 millions cu.m. (fig. 1-2-3).

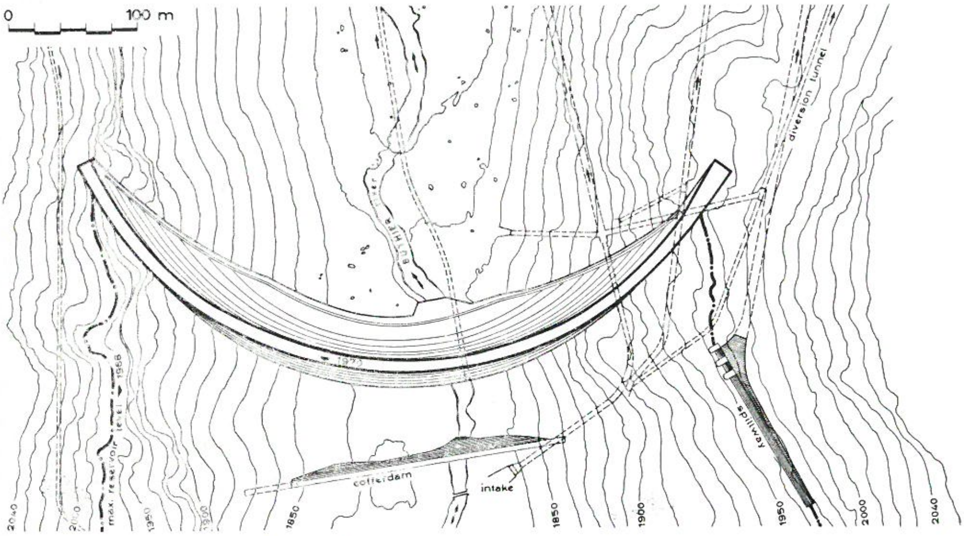

Fig. 1 — Plan of the Place Moulin dam.
Planimetria della diga di Place Moulin.

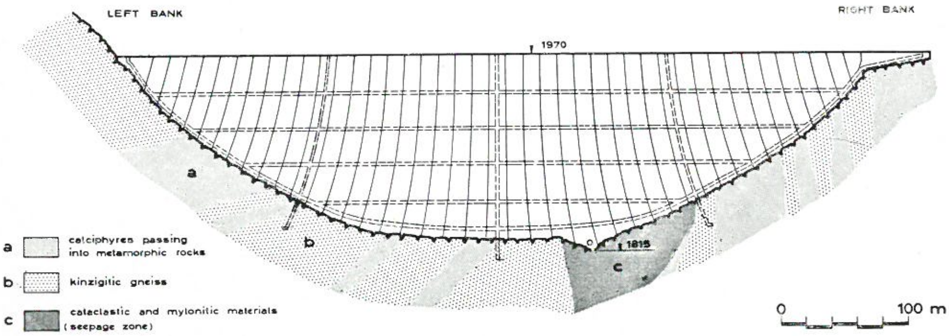

Fig. 2 — Section along the axis of the dam. Outline of the foundation bedrock.
Sezione longitudinale della diga. Profilo della roccia di base.

The dam has a max. height of 155 m, a crest length of 678 m and a base length of 200 m.

The bedrock is formed by alternations of the metamorphic crystalline Valpelline series (fig. 2) mainly consisting of:

a) calciphyres passing into pyroxenic-amphibolic metamorphic rock

b) Kinzigitic gneiss

c) fractured and laminated rock layers (consequent to high tectonic stresses) with interbeds of cataclastic and mylonitic materials.

The main formation of type *c*) rock traverses the foundation almost radially dipping from the foot of the right bank towards the left bank. In this area said formation was removed on a depth of $6 \div 10$ m and replaced by a concrete plug.

Also a minor pocket in the downstream part of the foundation was partially removed and also filled with concrete.

Both plugs were provided with grouting galleries and shafts.

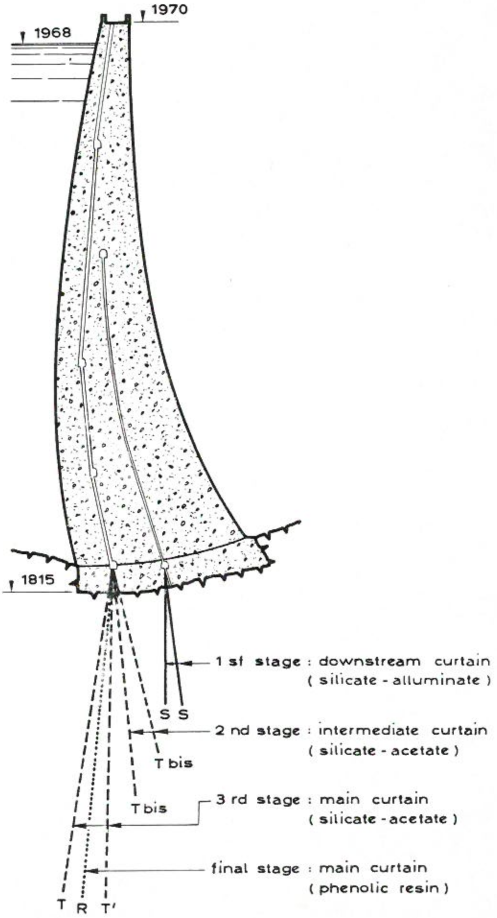

Fig. 3 — Cross section of the dam pattern of grout holes.

Sezione trasversale della diga e schema dei fori di iniezione.

The seepage water flowing downstream through the cataclastic-mylonitic zone was drained to a well sunk 3 m below the river bed, where it was periodically measured.

After intensive grouting carried out during 1963-1964-1965 (20'000 m of hole drilling, and 1'800 tons of cement in the last two years) the seepage flow was still remarkable (of the order of 10 liters per second) as shown in fig. 4.

According to the data obtained by accurate instrumentation (1) it was reckoned that the seepage was not such to affect the stability of the dam. Nevertheless it was decided as a safety measure to carry out a multi-stage chemical treatment applying recently developed procedures.

2. PRELIMINARY TESTS

2. 1. Laboratory tests prior to chemical grouting

Preliminary investigations were carried out to select the most adequate procedure for the treatment of the cataclastic-mylonitic materials where residual permeability had to be reduced.

Typical grain size curves shown in fig. 5 indicate a rather wide range of distributions, i.e. from graded silty sand with some gravel to fine-medium silty sand. The silty fraction is variable from 13% to 30% while the clay content is nil or negligible.

The prevailing permeability is of the order of 10^{-4} cm/sec.; anyhow some lower values (10^{-5}) have been measured in the finest non-cohesive layers.

Representative samples taken after the previous grouting stages (carried out with extra-fine cement suspensions at very high pressures) showed a net of thin grout lenses created by rupturing and some local compaction of the sandy-silty materials, but no substantial reduction of permeability.

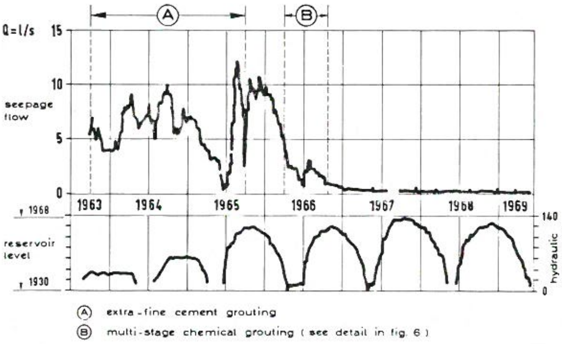

Fig. 4 — Seepage flow related to grouting periods and reservoir levels.

Andamento delle portate filtranti in rapporto ai periodi d'iniezione ed alle quote di invaso.

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(1) REBAUDI A.: « Behaviour of Place Moulin archgravity dam during the first reservcir test fillings » X Congrès des Grandes Barrages, Montreal 1970, Q. 38 - R. 30.

According to the grain size range, the following types of chemical solutions were considered for laboratory testing:

a) diluted sodium silicate with inorganic reagent (sodium alluminate)

b) diluted sodium silicate with organic reagent (ethyl acetate)

c) pure solution of phenolic resin (resorcin-formaldehyde in presence of a catalyst).

The first two types of grout had an initial viscosity of the same order (10 ÷ 20 cP), but a quite different final strength. In fact solutions *a*) produce soft gels that can be utilized only for impermeabilisation, whilst medium-hard gels are obtained from mixtures *b*) that are also fit for strengthening (15 ÷ over 30 kg/cm^2 compressive strength of treated soils it depending on dilution).

Laboratory tests revealed that grouts *a*) and *b*) had a satisfactory penetrability in some samples but could hardly impregnate the finest range of soil and tended to rupture the samples.

A homogeneous impregnation of finer material was obtained with pure solution *c*), having a constant viscosity of a few centipoises until a fixed time of polymerization. The compressive strength of a few centipoises until a fixed time of polymerization. The compressive strength of treated silty sands was of the order of 15 ÷ 20 kg/cm^2.

2. 2. In situ tests

Two test plots have been selected for a large scale check of the laboratory data.

The soft gels (silicate-alluminate) were not tested in situ, since they

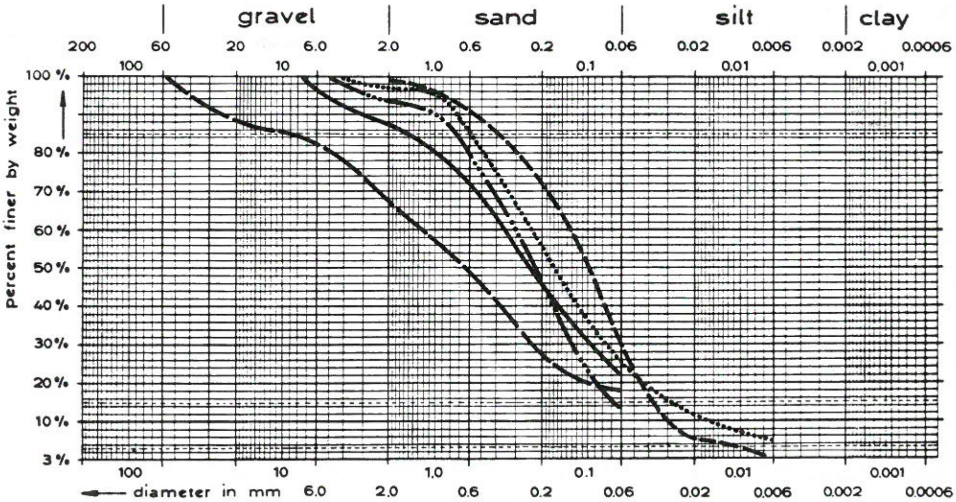

Fig. 5 — Typical grain size curves of mylonitic-cataclastic materials.
Curve granulometriche tipiche di materiali Milonitici-Cataclastici.

would not play a primary role in the proposed treatment as we shall see later. On the other hand their penetrability was already well known at that time.

Silicate-acetate and resorcin-formaldehyde were injected separately in two similar plots from the plug gallery crossing the main cataclastic-mylonitic zone. In each plot 3 holes 18 m deep were drilled, starting from the apexes of a triangle with a base of 2,50 m and a height of 1,00 m. The following average quantities have been injected per meter of hole:

— silicate-acetate solution: 780 l/m

— phenolic resin solution: 730 l/m.

2. 3. Control tests

In the center of each test plot, a control hole was drilled by means of double tube core barrels. Many satisfactory samples were taken in previously non-cohesive materials, which appeared well treated and consolidated.

The results of preceding laboratory tests (para. 2. 1) were visually confirmed, as concerns the better penetrability of resin solutions but also the opportunity of a combined use of more viscous cheaper mixtures such as diluted silicate solutions.

Laboratory tests on samples of grouted soil gave permeability values ranging from 10^{-6} to 10^{-5} cm/sec thus corresponding to a reduction of 10 to 100 times in comparison with previous results. Some samples kept under high hydraulic heads during many weeks showed the stability of the grouts; the seepage water was perfectly clean and no long-term increase of permeability was recorded.

3. CHEMICAL GROUTING

3. 1. General design criteria

According to the results of preliminary investigations and tests, the following types of chemical grouts have been used for adequate impermeabilisation and consolidation of cataclastic-mylonitic materials underlying the dam foundation:

a) colloidal solution of diluted sodium silicate with inorganic reagent (sodium alluminate) to form soft gels

b) colloidal solution of diluted sodium silicate with organic reagent (ethyl acetate) to form hard gels

c) pure solution of phenolic resin (resorcin-formaldehyde) with very low initial viscosity and a medium-hard final consistency.

The treatment has been carried out by means of several rows of holes (fig. 3) drilled with different slopes (0 to 25%) and depths (30 ÷ 80 m) into the bedrock from two galleries (downstream and upstream):

— (*S*) *holes* at 2 m intervals, alternately vertical and inclined (12% downstream), drilled about 30 m into the rock from the downstream gallery

— (*Tbis*) *holes* at 2 m intervals, with two alternate slopes (10% and 25% downstream), to depths of 45 ÷ 55 m into the rock; these holes and the following ones were drilled from the upstream gallery, as shown in fig. 3

— (*T*) *holes* at 2 m intervals with a 16% slope upstream penetrating about 80 m into the rock

— (*T'*) *holes* with the same spacing and depth as (T) but a slope of 3% upstream

— (*R*) *holes* at 2 m intervals, 70 m deep, having an intermediate slope between (T) and (T') rows, i.e. 9%.

The (S) holes were used for silicate grouting in order to form a downstream curtain such as to minimize grout leakage during the subsequent stages of the treatment.

A secondary downstream curtain was formed by silicate-acetate grouting through (Tbis) holes.

The main treatment had been carried out by injecting first silicate-acetate grouts (T and T' holes) and finally the most penetrating mixture (phenolic resin) through the intermediate (R) holes.

Some local grouting with extra-fine cement suspensions was required during the above mentioned stages in the most pervious spots.

The total thickness of the grout curtain (between rows S and T) was so designed as to obtain high head losses in the residual seepage water and a considerable reduction of uplift pressures.

3. 2. Silicate-alluminate grouting

An average amount of 216 liters per meter was injected through 35 holes (S) during the first treatment stage, from march to may 1966.

3. 3. Silicate-acetate grouting

In the second and third stage of the treatment (from march to november 1966), the following average takes of silicate-acetate solution were recorded:

(Tbis) : 141 liters per meter in 41 holes

(T + T') : 216 liters per meter in 82 holes

The unit grout take of (T + T') holes was higher than that of (Tbis) holes because the former reached into deeper more pervious layers.

3. 4. Phenolic resin grouting

The final treatment stage was carried out from august to november 1966. An average quantity of 70 l/m of resin solution was injected through 50 holes (R).

Considering the greater penetrability of this mixture in comparison with that of silicate-acetate solutions (5 times more at least) the lower unit take (70 against 216 l/m) is an indicative factor of the efficacy of the multi-stage treatment. In fact the purpose was to minimize residual permeability with the least consumption of the most expensive type of grout.

A supplementary treatment with resin solution was carried out from the plug galleries which followed the cataclastic zones in the up-downstream direction. An average volume of 207 l/m was injected through 21 holes, about 40 m deep. Highly concentrated grout takes showed that this additional treatment intercepted an important seepage path, as confirmed by the subsequent drawdown recorded by downstream piezometers.

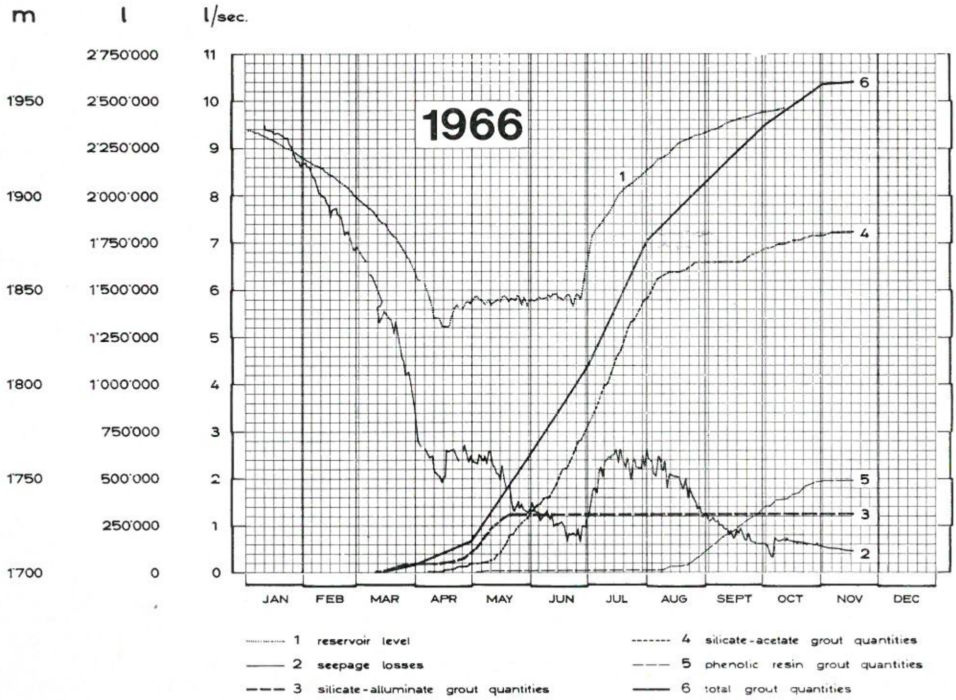

Fig. 6 — Influence of chemical grouting on seepage.

Influenza del trattamento chimico sulle filtrazioni.

4. INFLUENCE OF GROUTING ON SEEPAGE

After intensive treatment with extra-fine cement suspensions in several stages from 1963 to 1965, the seepage flow was still of about 10 liters per second, as shown in fig. 4.

The progress of the works and the effect of subsequent chemical grouting are detailed in fig. 6, covering a period of one year (1966).

The following remarks can be made:

- from january to mid-april the emptying of the reservoir had reduced the seepage losses to a minimum of 2 l/s; this residual flow was likely due to a delayed effect of drawdown and partly to ground water flowing outside the reservoir

- in the second half of april a limited impounding produced a sudden increase of seepage up to 2,7 l/s

- at nearly constant level of the reservoir the seepage flow began to decrease in the second half of may, dropping to 0,7 ÷ 0,8 l/s at the end of june. At this date the first stage of chemical grouting (soft gel downstream curtain) had been completed, while silicate-acetate grouting was under way

- the rapid impounding of the reservoir which followed produced a sudden increase of seepage losses reaching a peak of 2,6 l/s by mid-july, but two weeks later the downstream flow began again to decrease while the reservoir level was still rising and silicate-acetate grouting was under way

- then a decisive drop of seepage followed during the final stage of grouting (phenolic resin)

- at the completion of the treatment (november) a flow was recorded of about 0,5 l/s, it being 20 times smaller than that measured the preceding year under the same hydraulic head.

The diagram of fig. 4 confirms the efficacy and the stability of the multi-stage chemical treatment during further impoundings and drawdowns of the reservoir.

The residual seepage was reduced to a few tenths of liter per second.