KÖLNBREIN DAM
A special solution for a special problem

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1. The Kölnbrein Dam

The Kölnbrein Dam, on the Malta-River in southern Austria, owned by the Österreichische Drau Kraftwerke (Austrian Power Utility of the Drau River) is a 200 m high very thin arch dam. The foundation rock of the quite wide valley consists of a succession of crystalline rocks ranging from massiv granitic gneiss on the right bank to a more schistous gneiss on the left. In the bottom a quite schist formation crosses diagonally the dam foundation.
A very characteristic of the valley section is its about 150 m wide flat bottom, which contributes to increase to length of the dam crest up to 626 m. Fig. 1

Doubtless, the total water load of 54 GN (or 5.4 Mio tons) acting on the Kölnbrein Dam, is one of the highest loads on arch dams world wide.

Considering the concrete volume of about 1.6 Mio m³, the slenderness coefficient of the Kölnbrein dam reaches the value of 17.5 and places it on the hedge of the field of the existing large arch dams according to fig. 2.

The dam was built during the years 1971 to 1977. At its maximum operation level of 1902 ms1, it will impound a volume of 200 Mio m³ water.
2. Problem and former tentative efforts to solve it

During the first impounding in 1977, cracks formed in the upstream heel of the dam at a pond level of about 1860 that is 42 m below the maximum operational level. Fig. 3. Through the cracks in the central part of the dam, a flow of about 200 lt/sec entered the lowermost inspection gallery. At the same time the uplift pressure in the foundation reached about the water level of the reservoir.

It was therefore believed that the grout curtain had been damaged and possibly sheared off.

A number of actions were taken simultaneously or successively in order to try to reduce these uplift pressures as well as the mentioned water inflow. Among them one may mention the following:

- 1979 strengthening of the grout curtain with cement grout. Lowering the uplift through bored drains.

- 1980-81 polyurethane resin grouting. Freezing of the central part of the dam bottom during impounding and letting it melt during yearly drawdown.

- 1981-83 a concrete blanket covered by plastic sheets was placed on the valley bottom just upstream of the dam.

- 1984-85 the plastic sheets had to be repaired and extended. The grout curtain was regrutted as meanwhile new cracks had formed and the water inflow had temporarily increased again up to 1000 lt/sec

In spite of so many difficulties, the reservoir could nevertheless be filled by 90% until 1984 while the maximum level was reached twice, in 1979 and in 1983.
Since 1984 the impounding is limited for safety reasons, to an
elevation of 1880 to 1885.
However it became clear with time that a radical solution for
repairing and strengthening the dam had intensively to be
searched for.

3. Finding the causes of the damages

The search of the causes of the problem just described was not
a simple one, as the case of Kölnbrein appeared to represent a
very special unprecedented complex of damages of an arch dam of
this shape and size.
A number of possible causes or concurrent factors were investi-
gated, discussed and analysed. A many of them could finally be
ruled out, and a more or less general agreement on the mecha-
nisms for the cracking could be found.

First of all it has to be recalled that this dam is a quite
large, very thin, heavily loaded structure. The flat valley
bottom eliminates almost any possibility of an arching action
in the lower part of the dam. Consequently the trasverse forces
in the central cantilevers near the foundation due to the water
pressure at maximum level, are very high reaching a peak value
of about 70 MN/m$^1$(7000 tons/m$^1$).

The corresponding average shear stress is of the order of 2 MPa
(20 kg/cm$^2$). Its peak value is theoretically 50% higher, and
approaches the ultimate strenghht on shear of the concrete.

The following peculiarities shall also be taken into considera-
tion.
First of all the shape of the vertical section of the dam produces tensile stresses at the lower part of the downstream face even under the only action of the dead weight.

Then, the grouting of the vertical construction joints between the dam blocks unavoidably opens them at least somewhat, thus deforms the dam towards upstream increasing the already mentioned tensile stresses. In the case of Kölnbrein the regrouting was repeated at different times with high pressures and very important grout takes.

The combination of these factors was the cause of forming a number of approximatively horizontal cracks, or opening of joints between concrete lifts, starting from the downstream dam face and entering quite deep in the concrete mass. It is well understood that these cracks will modify the shear stress distribution across the dam sections with a stress peak forming at the crack tip. The maximum tensile stress induced in the concrete mass, is inclined and reaches an extreme high level of intensity, thus producing the already mentioned inclined cracks in the upstream heel of the dam.

One has also to take into account that, the deformation of the arch dam under the hydrostatic load produces a general tilting of the structure transferring the load from the valley bottom to the valley flanks and reduces, that way, the vertical load in the central part of the dam. This effect is particularly important in the case of a wide flat valley bottom just like in this case. At last the deleterious effect of the water pressure entering the cracks and extending them should not be forgotten.
4. Search for a solution

As the supplementary actions described above did not lead to any satisfactory improvement in the dam behaviour, the High Water Right Authority, in 1984, reduced the permissible water level in the reservoir first to 17 m and finally to 22 m below the maximum operating level of 1902 m. This led the owner to search for a radical remedial project with the following objectives:

- increasing the dam stability within the cracked zone and
- ensuring future unrestricted reservoir operation.

As already mentioned, near-horizontal cracks had developed in the lower downstream portion of the dam. During reservoir filling, a redistribution of forces took place which led to a continuous reduction of the vertical forces in the central portion of the dam, while at foundation elevation the downstream directed transverse forces were steadily increasing.

Therefore as the water level rises in the reservoir, the ratio of the transverse forces to the normal ones deteriorates rapidly. This phenomenon finally caused the centre blocks of the dam to shear off near the base, with the surfaces of failure forming a complex pattern which combines the above mentioned near horizontal cracks on the downstream side with steep cracks towards upstream, as to be seen at fig. 3.

For this reason an efficient remedial action would have to aim at either increasing the vertical normal force substantially or reducing the transverse force correspondingly in the critical zone of the dam, in such a way that the ratio between the two would not exceed an allowed limit. In addition, provisions should be taken to ensure that the range of the moments between empty and full reservoir condition be restricted so that the resulting force remains within the core of the cross sections.
5. **Project**

In order to satisfy these conditions, various possibilities were developed and studied in detail, which all designed to increase the vertical or to reduce the transversal force, or to combine the two effects. Thorough study and consideration of advantages and disadvantages of the various proposals finally led to the selection of a project providing for a heavy downstream arch-gravity structure as thrust block propping the dam. The thrust block will take up a share of the water load in the order of 12 GN (1.2 Mio t) reducing at the same time substantially the transverse forces in the dam cantilevers.

If the thrust block is to offer an important resistance, its connection with the dam can not be too rigid, as otherwise the problems arising at its upper edge would be similar to those the new structure is intended to solve at the very dam base. **Fig. 4.**

A solution for these conflicting requirements of stability and rigidity was found by providing a joint or gap of variable opening between dam and thrust block. During reservoir filling, the gap will close progressively from the bottom upwards in accordance with characteristic curves computed in advance and, if necessary, adjusted according to the experiences gained during the first phases of partial impounding.

Neoprene pad bearings especially designed for this purpose are provided to ensure an easy adjustment, in the condition of an unloaded dam and, hence, an open gap, while when contact pressure between the two structures has been established, the pads cannot be manipulated any longer, neither due to faulty maneuvering or human and mechanical error, nor maliciously.

The precise specification of the point of closure for each of the more than 600 pads, that is the determination of the reser-
voir levels at which each support enters into contact with the
dam and is intended to start assuming loads, constitutes there-
fore a main element of the dam strengthening project.

Another advantage of the massive thrust block selected lies in
the fact that the very important weight of the structure sub-
stantially improves the stress and stability conditions in the
rock mass downstream of the dam.

Apart from the thrust block, the strengthening project provides
for the filling of the cracks by grouting. Actually, the grou-
ting scheme is one of the main aspects of the project and also
of the stability analysis. The grouting is intended to ensure
the monolithism in terms of transfer of forces and watertight-
ness in the cracked zones both of the foundation rock and the
concrete.

The thrust block and in particular the magnitude of the forces
acting on it have been selected in such a way that during the
reservoir filling and drawdown cycles the stresses caused in
the lower portion of the concrete structure are limited to a
narrow and optimal range. Primarily, however, provisions have
been taken to ensure that such loadings will not cause any ob-
jectionable tensile stress.

A fact that is not to be overlooked is, however, that the final
state of stress will be influenced by the manner in which the
grouting is performed. The sequences and the timing of the
grouting operations as well as the procedures and pressures
used and the grout volume taken will be important factors con-
ditionning the success of the repair works.

The grouting operations will be carried out in seven phases
termed "M to R". A drainage system will be provided in a phase
called "T". Fig. 5.
A hyperbolic relationship between the volume taken and the grouting pressure forms the guideline for the cement consolidation of the rock mass using only one tick water cement mix. The pressure to arrive at will constantly be reduced as a function of the amount of grout already taken with certain additional limitations for pressure and volume. Fig. 6. The parameter of the hyperbola; that is the product of the grout pressure by the grout volume is defined as the "Grouting Intensity Number" (GIN).

For the epoxy resin injections into the concrete cracks it is primarily the volumes to be pumped in, that have been computed as a function of the crack width and the desired reach, which depends to the distances to the next boreholes.

Dam monitoring during the grouting operations will concentrate on the behaviour of the concrete mass in the vicinity of the grouting operations as well as on the overall deformation of the two structures; arch and thrust block. No need to emphasise that an appropriate instrumentation will provide for an accurate monitoring of the grouting. The existing instrumentation will be complemented for this purpose; the objective being to observe the widening of the cracks during the grouting operations so as to prevent their excessive opening.

Always based on the above idea, the project was refined in a number of steps and finalized for execution. It is obvious that the peculiarity of the damages observed and of the problem to be solved led to a quite special design. It should however be stressed that all the structural elements proposed are well experienced so that no unforeseen events is likely to occur at construction time nor during the future dam operation.
6. The construction

As the final design of the remedial works was approved by the High Water Right Authority in July 1988, the decision to build was taken by the owner in February 1989. The contract was awarded and the construction works could start the same summer.

To date, the entire concrete volume has been placed. The installation of the neoprene pads and the grouting works will represent the main activities of the year 1991. In the following years additional grouting is likely to be done.

It is foreseen to fill the reservoir in yearly steps so to reach again the maximum operational level in the course of the year 1994.

During the ICOLD Congress in Vienna, some study tours will provide the opportunity to visit this very interesting and unusual construction site.

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Remedial Project for Kölnbrein Arch Dam
Design and Construction
To be published on the occasion of the ICOLD Congress in Vienna, June 1991
Figure 1
Kölnbrein dam
Main layout
Figure 2
Coefficient of slenderness $C$ vs. height of the dam $H$, for a number of large arch dams
Figure 4
Main section of dam, thrust block and zones to be grouted
Figure 5
Main grouting phases for Kölnbrein repairs
Figure 6
Example of a Grouting Specification

\[ \text{p} = \text{grouting pressure} \]
\[ \text{V} = \text{grout take} \]
\[ \text{p} \cdot \text{V} = \text{grouting intensity number (GIN)} \]