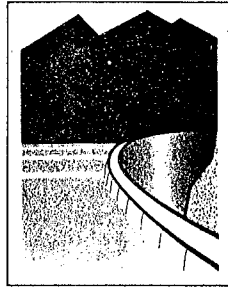


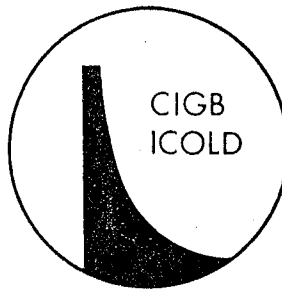
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Reassessment and Rehabilitation of the San Giacomo di Fraele Dam

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SUMMARY

The operational conditions of the 42 years old San Giacomo di Fraele Dam have undergone significant modifications not foreseen in the original design. The paper presents the investigations carried out to evaluate various safety aspects related to the existing buttress dam. Furthermore, the relevant characteristics of the rehabilitation project based on the results of the previous analyses are briefly described. As a result of the modified operational conditions of the dam, the rehabilitation project includes extensive concrete works as well as protective measures insuring a long term operation of the dam in agreement with present safety requirements.

INTRODUCTION

The Azienda energetica municipale di Milano (Aem) started nearly 10 years ago a detailed check-up program of the dams operated in the Valtelline valley. In addition to safety assessment studies of the principal dams (Cancano, San Giacomo, Val Grosina, Fusino and Sernio) attention was paid to the environmental aspects related to the hydroelectric power plants, some of them being located in a national park (Parco Nazionale dello Stelvio).

The need to improve and standardize the monitoring of the dams appeared since the beginning of the check-up program and resulted in an extensive monitoring update project started approximately 7 years ago. This project included the review and partial substitution of the existing instrumentation, the design of an effective data transmission system as well as the development of numerical models and of integrated monitoring programs developed by ISMES (Istituto Sperimentale Modelli e Strutture) of Bergamo. The actually nearly completed update of the monitoring system, offers the Aem personnel a permanent overview of the dams behaviour both during normal and exceptional operational conditions.

In addition to the monitoring aspects, the check-up program includes the assessment of the actual operational conditions of the main Aem dams focused on safety and ageing aspects. It must be mentioned that excepted some minor plants constructed in recent years, the hydroelectric development of the upper Valtelline was achieved approximately 30 years ago. Within this investigation frame, priority was given to the San Giacomo di Fraele dam, one of the oldest large Italian dams completed in 1950. The Aem commissioned in 1987 to a consortium of consulting engineers the evaluation of the dam's operational conditions, including the design of all rehabilitation works required to operate the plant in full agreement with the present Italian dam regulation.

The methodology adopted for the analysis as well as the selection of the most adequate rehabilitation project according to the characteristics of the structure and to modern safety requirements are the main topics handled in the paper presented.

1. REVIEW AND CHARACTERISTICS OF THE DAM

The San Giacomo di Fraele dam is situated not far from the city of Bormio in the Fraele valley at the springs of the Adda river. The reservoir of 64 hm³ total capacity with a normal water level at elevation 1949.0 m s.l. is fed by the run-off of a 151 km² catchment area.

The dam, built between 1940 and 1950, consists of a central 375 m large buttress dam and of massive gravity structures on both abutments. The dam crest, with a total length of 971 m, is at elevation 1951.5 m s.l. resulting in a maximum dam height above the lowest foundation level of 95.7 m. The total concrete volume including the massive abutments is about 600'000 m³. At its completion, significantly delayed due to world war II events, the dam turned out to be the most important Italian structure for its concrete volume.

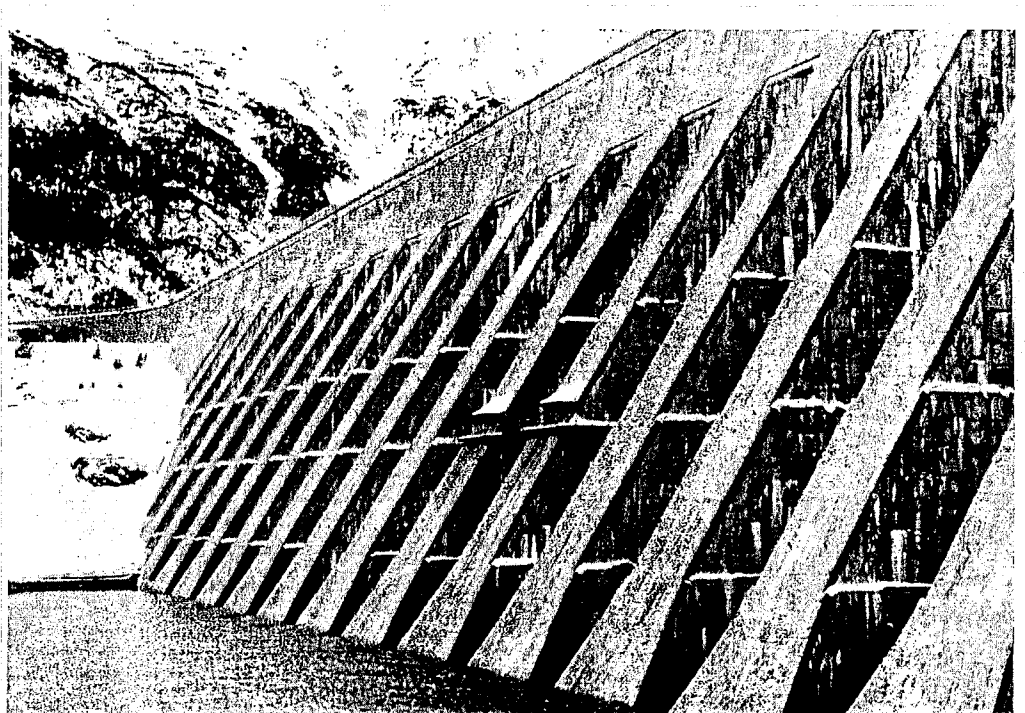


Figure 1. San Giacomo di Fraele dam: downstream view of the buttress dam, the right massive gravity abutment and part of the downstream Cancano reservoir impounded in 1957.

The buttress dam is composed of 25 masonry faced solid head buttresses, at 15 m distance, with a web thickness varying between 4.8 and 8.6 m from the top to the bottom of the highest buttress. The dam is founded on hard and generally impervious banks of dolomitic limestone dipping downward into the reservoir at approximately 10°. An unlined exploratory gallery placed 15 m under the dam foundation and permanently accessible attests the outstanding rock quality.

During the construction of the dam, several modifications were introduced in the original design. In particular at an advanced construction phase, the crest elevation was increased by 8.5 m allowing in a 7 m raising of the normal water level. In addition the planned downstream closure of the cells between the buttresses using pre-casted concrete slabs was finally abandoned. Figure 2 shows a cross section of the highest buttress in the vertical joint between two buttresses as well as typical horizontal sections at various elevations. It must be outlined that with an upstream slope of 3% and a downstream one of 62% the ratio between total width and height of the buttresses is significantly smaller than the usually adopted values for similar structures.

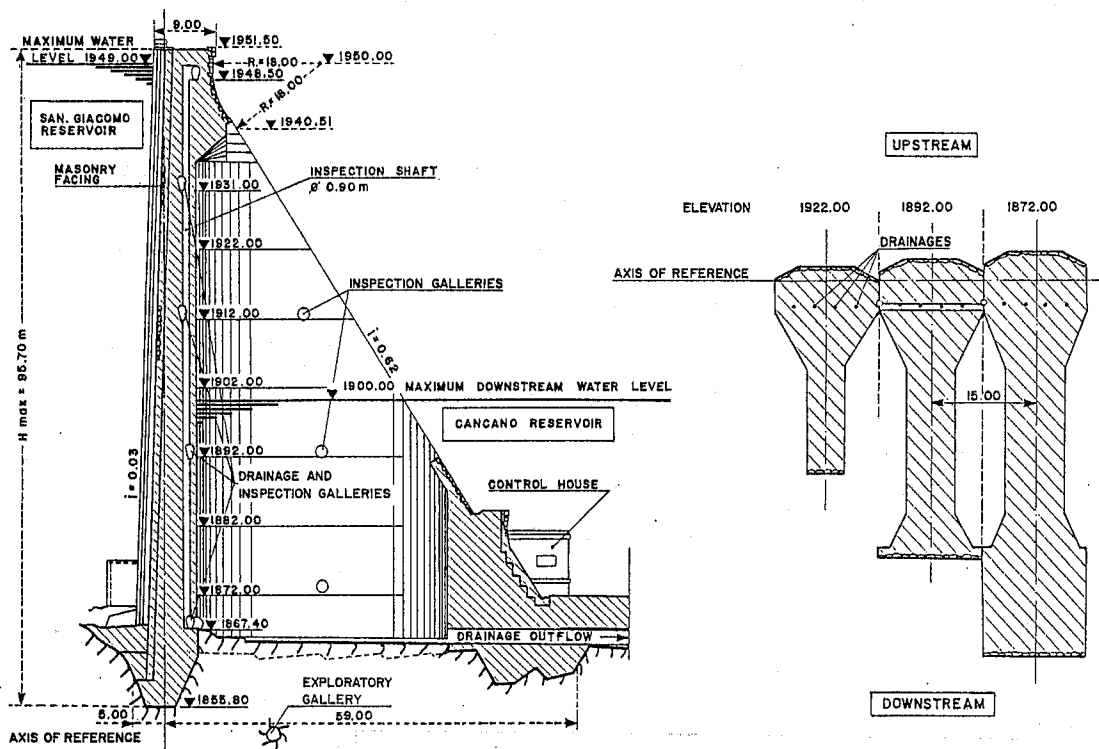


Figure 2. San Giacomo di Fraele dam. Section in the vertical joint of the highest buttress and horizontal sections at various elevations.

Approximately 4 km downstream of the San Giacomo dam, the Aem completed in 1956 the construction of the Cancano arch gravity dam with a crest elevation at 1902 m s.l. The impounding of the Cancano reservoir with a normal water level at elevation 1900 m s.l., resulted in a partial submersion from downstream of the central buttresses of the San Giacomo dam as shown in figures 1 and 2. This submersion starts usually at the end of June attaining its maximum height of 35 m above the foundation level at the beginning of September and decreasing again in December. Excepted some minor modifications of the dam instrumentation, no measures were taken to protect the dam and to limit the negative effects of the unforeseen downstream submersion. As consequence of the submersion the uplift increased significantly in dam sections

situated below elevation 1900 m s.l., affecting thus the stability conditions of the buttresses. It must nevertheless be outlined that the displacements of the dam were quite normal with very small non reversible components even after the impounding of the Cancano reservoir. In addition, the periodical downstream water pressure and the increased uplift had no practical influence on the recorded dam displacements.

A further consequence of the submersion in winter is the superficial degradation of the concrete on the downstream dam face in particular on the lateral faces of the buttress webs. The severe climatic conditions with a temperature amplitude up to 60°C and long frost periods combined with the periodical saturation of a relatively porous concrete resulted indeed in an acceleration of the superficial degradation of the concrete especially at the toe of the central buttresses. Although the formation of thick ice cover between the buttresses webs was successfully avoided by hot water jets, and despite the still satisfactory mechanical properties of the concrete, the constant progress of the degradation phenomenon was confirmed by periodical field inspections carried out by the Aem.

2. PURPOSES AND METHODOLOGY OF THE ASSESSMENT STUDY

Although the behaviour of the dam resulted satisfactory during more than 40 years of operation, the increased downstream uplift and the progressively appearing ageing phenomena made the Aem to charge in 1987 a consortium of consulting engineers to carry out a detailed evaluation of the effective conditions of operation of the San Giacomo dam. The purposes of the investigations may be summarized as follows:

- Evaluation of the relevant safety aspects of the actual structure, considering namely static, hydrologic, hydraulic and monitoring aspects.
- Design of the rehabilitation works required to operate the dam, according to present safety rules, in agreement with the present italian regulations for dams for a period of at least 50 years.

In order to satisfy the requests of Aem, the analysis included principally field investigations, numerical analyses as well as the design of the rehabilitation works. Figure 3 shows schematically the procedure adopted as well as the various studies and investigations carried out.

Despite of the systematic classification of the existing documentation on the dam in the Aem archives, the search for the "as-build" drawings and the setting up of the historical sequence for the studies carried out and the reports prepared prior and after the dam construction resulted quite laborious. An essential contribution for a better comprehension of the adopted construction methods was offered by few persons involved in the dam construction.

In matter of the field investigations, the information obtained was compared with the field data of previous campaigns resulting finally in a complete overview of the destructive and the non destructive test results recorded during more than 40 years of operation.

The numerical analyses include principally the definition of the stress distribution in the buttresses and the foundation under static loads for various conditions of operation, the statistic evaluation of the test results, and finally hydrologic and hydraulic evaluations in order to determine the flood characteristics and the behaviour of the dam under extreme conditions.

The relevant conclusions resulting from experimental and numerical investigations important for the design of the rehabilitation of the dam may be summarized as follows:

- The mechanical characteristics of both the concrete and the foundation rock may be considered satisfactory despite localized high permeability of the concrete mass.

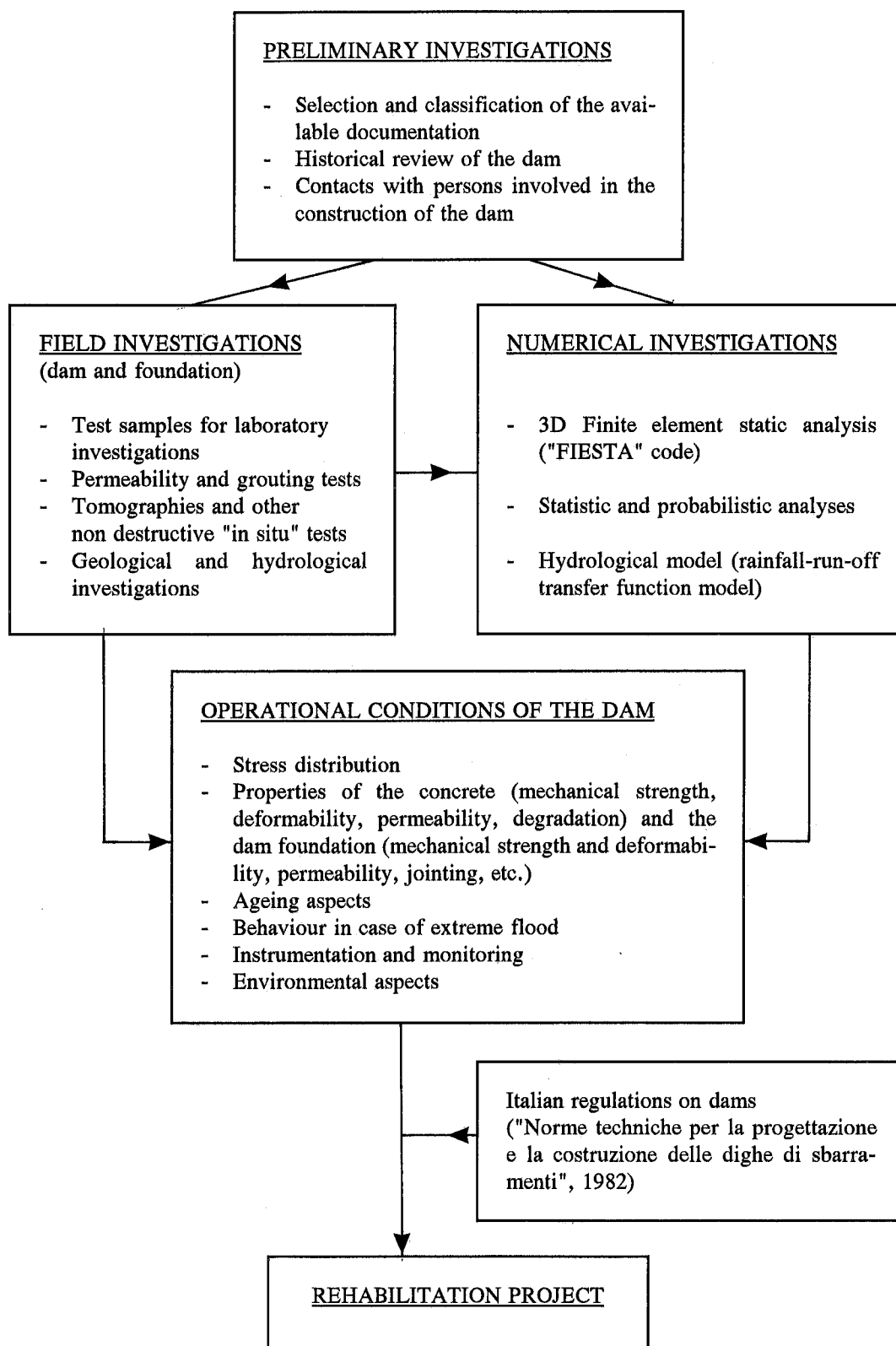


Figure 3. San Giacomo di Fraele dam. Schematical chart of the assessment study and the rehabilitation project.

- From the ageing point of view, the relevant phenomenon concerns a degradation of the concrete averaging a depth of 20 cm and the ineffective drainage system of the dam and the foundation due to partially or completely plugged drainage pipes.
- The increase of the uplift results in a significant decrease of the ratio stabilizing to destabilizing forces leading to an activated shear angle at foundation level of $\varnothing=45^\circ$, neglecting thereby the possible contribution of the cohesion.
- Tensile stresses with maximum values up to 0.54 N/mm^2 were obtained both along the upstream and the downstream faces. The maximum compression stresses reach 2.52 N/mm^2 at foundation level of the upstream face at empty reservoir.
- As confirmed by the measurements of the dam displacements, the numerical model has shown only a moderate effect of the downstream water pressure on the calculated dam deformations.

Despite the satisfactory static behaviour of the San Giacomo dam practically not affected by the Cancano reservoir, the analyses indicated that some requirements of the Italian dam regulation are only partially fulfilled by the present conditions of operation of the dam. In particular, the water pressure acting on the downstream dam face resulted to be a determinant factor from the regulation point of view. The rehabilitation project was therefore focused on the following aspects:

- Significant increase of the stabilizing forces in order to decrease the value of the activated shear angle.
- Slowing down and eventually stopping of the ageing phenomena, in particular as regards the concrete degradation at the downstream dam face.

3. MAIN ASPECTS OF THE REHABILITATION PROJECT

According to the previous considerations, the increase of the stabilizing forces required to reduce both the tensile stresses and the activated shear angle, is obtained by an increase of the buttresses weight combined with a significant reduction of the uplift.

The principal elements of the rehabilitation project, shown at figure 4, may be summarized as follows:

- Increase of the weight of the central buttresses by thickening the webs with two reinforced concrete slabs and providing an impervious closure of the space between the buttresses webs. The weight of the additional concrete represents approximately 13% of the buttresses weight at present time.
- Significant reduction of the uplift both by new drain holes and by an impervious closure avoiding the water from the Cancano reservoir to enter the space between the buttresses webs. A pumping system located at the lowest foundation level will collect the leakage from the downstream reservoir. In addition to the uplift decrease, the reduction of the temperature variation combined with permanently unsubmerged lateral faces of the buttresses webs will stop the degradation of the concrete surfaces.
- Drilling of a new drainage system in the buttresses head and the dam foundation according to the specifications of the Italian regulations on dams. In addition, in order to limit the seepage from the Cancano reservoir a 15-20 m deep grout curtain from the downstream berm, is included in the project (see figure 4).
- Replacement and complementing of the dam instrumentation and updating of the monitoring system presently used.
- Better integration of the structure in its natural environment including reforestation, demolition of unaffected buildings, and conservation of the same aspect as the existing buttress dam after the completion of the dam rehabilitation works.

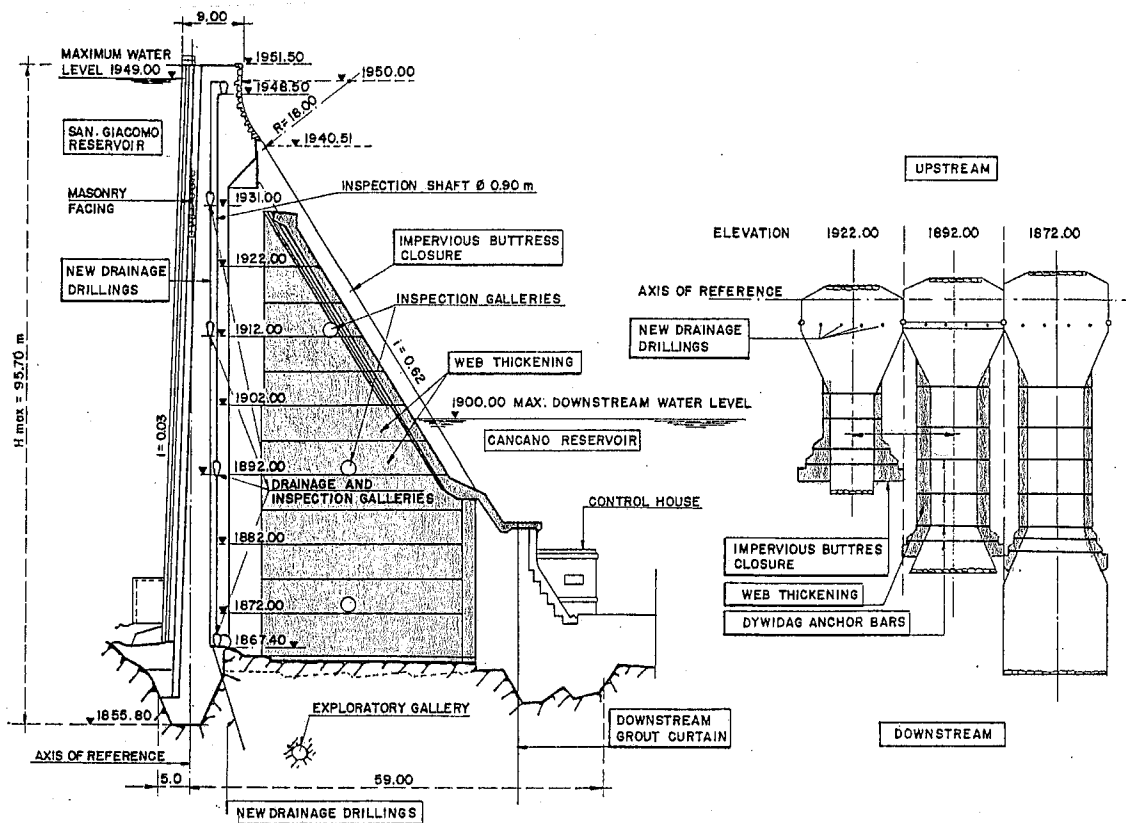


Figure 4. San Giacomo di Fraele dam. Principal elements of the rehabilitation project.

The connection between the new and the old concrete, is insured by prestressed anchor bars passing through the buttress webs as shown in the previous figure.

In addition to the works already mentioned, a series of minor maintenance works as the overhaul of the gates and localized repairs of the masonry facing are included in the project.

Globally the project involves the placement of approximately 60'000 m³ of concrete and 30'000 m of drillings with a total estimated cost of approximately £ 45'000 mio (~ US\$ 30 mio).

CONCLUSIONS

Based on the experience gained during the assessment studies and the design of the rehabilitation works of the San Giacomo di Fraele dam a few general conclusions are laid out hereafter.

The first aspect concerns the modification of the conditions of operation which may affect dams during their lifetime. These modifications, which cannot be foreseen in the original design may affect the safety of the structure. In particular, as indicated in the present study, an accurate monitoring of the dam under modified loading conditions is not sufficient to ascertain its safety, even if the modified loading conditions do apparently not influence the behaviour of the dam. Any relevant change of the conditions of operation of existing dams has therefore to be carefully evaluated by adequate safety assessment studies.

The second aspect concerns the distinction which has to be made between the fulfilment of national dam regulations and dam safety assessment studies. The present analysis indicated that the whole dam safety aspects cannot be included in regulations on dams. In particular, the local geologic and hydrologic conditions which are essential factors of the dam safety are taken into account only partially by dam regulations. It is therefore left to the engineer to appreciate and quantify by the most appropriate analyses the principal elements contributing to the dam safety. Various national regulations on dams include for example no indications on evaluation criteria of flood events leaving a total liberty on one of the most difficult and essential safety parameters.

Finally, as for the San Giacomo di Fraele dam, in many cases old dams are presently considered structures of historical value in order that their appearance has to be conserved as much as possible. Rehabilitation projects have therefore not only to consider operational and safety requirements but equally aesthetic and architectural aspects.

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