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# THE SEISMIC SAFETY ASSESSMENT OF A MULTIPLE ARCH DAM

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**Abstract**: *As in many European countries, today in Italy there are few possibilities to design and build new dams. In particular, the construction of buttress (both solid or hollow) or multiple arch/slab dams is practically abandoned because they have shown in time several problems, namely cracks. On the other hand, there is a strong need to keep existing dams in safe service conditions, considering also the effects of seismic loadings, not foreseen during the design.*

*In order to evaluate the health of an existing infrastructure, it is necessary to define the external acting forces and to analyse the structural response towards these loads by means of mathematical models of the dam-rock-reservoir system.*

*The Italian standard (D.M. 26 June 2014) is indeed focused into this aspect by suggesting the development of a reference dam model (e.g., based on the finite element method), able to analyse the response of these hydraulic structures under static and seismic actions, higher than those applied in the design phase, thus leading to more stringent conditions.*

*Therefore, the finite element models are used to evaluate and predict possible structural deterioration, which can imply abnormal behaviour and consequences, such as, for example, cracks and displacements due to environmental conditions (thermal or chemical phenomena) and aging.*

*First, this article presents an overview of the problems concerning buttress or multiple arch/slab dams and highlights the importance of the numerical models, which allow to study their safety under seismic loadings.*

*Then, finite element analysis of an Italian multiple arch dam, subject to static and seismic loads, is presented.*

*The response of this hydraulic structure is studied considering different results: principal stresses, compared with standard limits; sliding coefficient of horizontal sections (defined as the ratio between horizontal and vertical forces), which must both be less than one; eccentric axial force analysis.*

## 1. Introduction

In Europe the need to guarantee the safety of existing dams is strongly felt. Indeed, a service life that often reaches or exceeds 5/6 decades can lead to possible problems of aging.

The design, construction and supervision of dams are regulated by current national and regional regulations, considering the hydraulic structure dimension (Evangelisti, 1982).

In ancient times dams were mainly built for the storage of water intended for irrigation and water supply. With the civilization development, these needs also extended to flood and sediments control, navigation, aqueduct support and, above all, hydropower generation (e.g., in Italy hydropower is still the main renewable source and accounts for 15-17% of the national electricity production, Figure 1). The multiple use of water of dam reservoirs represents a necessity, but also an opportunity, for countries development, as the population would be able to obtain both domestic and economic benefits from a single investment. The need to exploit the water resources for the energy production accelerated the construction of increasingly large dams (Figure 2). Italy, for instance, went from a dozen of dams at the end of the nineteenth century to almost 400 large dams in the first half of the twentieth century. At present, the large dams in operation are 531.

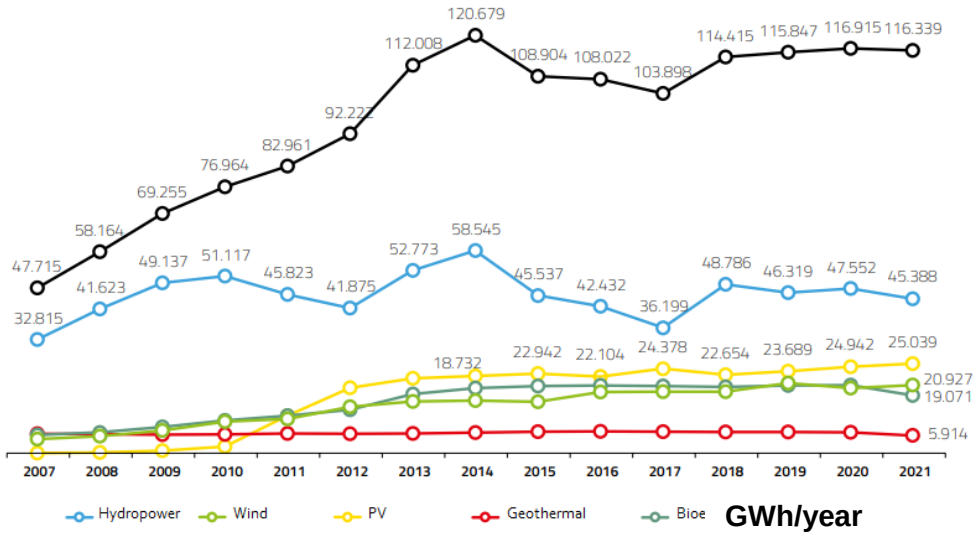
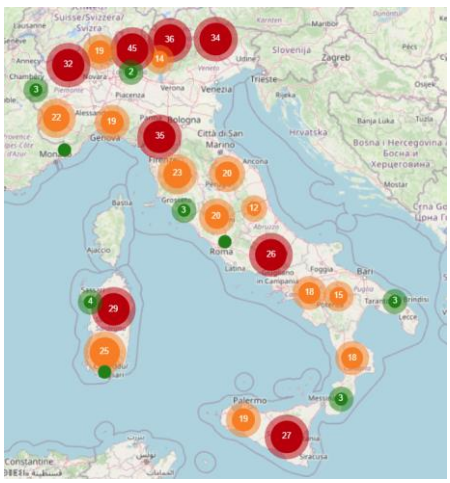



*Figure 1. Annual hydroelectric power production in Italy.*



**Legend**

The small green point means 1 dam; the number reported in all the other points stands for the number of dams in that area.

| | | |
|---|---|---|
| NORTH | = | 46 % |
| CENTER | = | 32 % |
| SOUTH | = | 32 % |
| *Total* | | *531 dams* |

*Figure 2. Location of dams in Italy.*

Existing dams are controlled through monitoring systems and periodic inspections, with the aim of promptly identifying any anomalous behaviour, which must subsequently be interpreted to evaluate the causes (Brownjohn, 2007; Ardito et al., 2008; Bukenya et al., 2014). The physical-mathematical modelling of a dam-rock-reservoir system is also part of the investigations. Under known external actions, the comparison between the structural response of the finite element model (which predicts the expected effects) and the actual dam response described in terms of monitoring data represents a fundamental interpretation of real phenomena (Mirzabozorg et al., 2014; Colombo et al., 2015; Colombo et al., 2016).

There are several types of dams, defined according to the Italian regulation (DM2014): gravity, arch, slab/arch, earth fill, mixed. The first slab/arch dams were built in the first twenty-five years of the 1900. The collapse a mixed gravity and multiple arches dam (Gleno dam, Figure 3) in 1923 led to build more massive hydraulic structures (e.g., gravity dams).

In this article an overview of the problems concerning buttress or multiple arch/slab dams is reported. Furthermore, the importance of the numerical models to evaluate their safety under seismic loadings is shown. Finally, finite element analysis of an Italian multiple arch dam, subject to static and seismic loads, is presented.

*Figure 3. Gleno dam (Italy): downstream face view after construction (left) [Source: Gleno Archive] and upstream face view after collapse (right).*

## 2. The main problems affecting buttress and slab/arch dams

Generally, the crack pattern of dams is related to thermal phenomena that could occur already during the phase construction, particularly in the case of buttress and slab/arch structures.

The aging of materials, due to environmental conditions or chemical phenomena, such as the alkali-silica reaction (Ingraffea, 1990; Thomas et al., 2013), shown in Figure 4, and the corrosion of steel rebars in slabs and multiple arches represent other issues. In addition, also the quality and the porosity of the material (concrete) contribute to aggravate its deterioration condition. Finally, other problems are related to possible loss of resistance to sliding (caused by the development of high uplift pressures), leakage through the upstream face and low resilience to seismic actions.

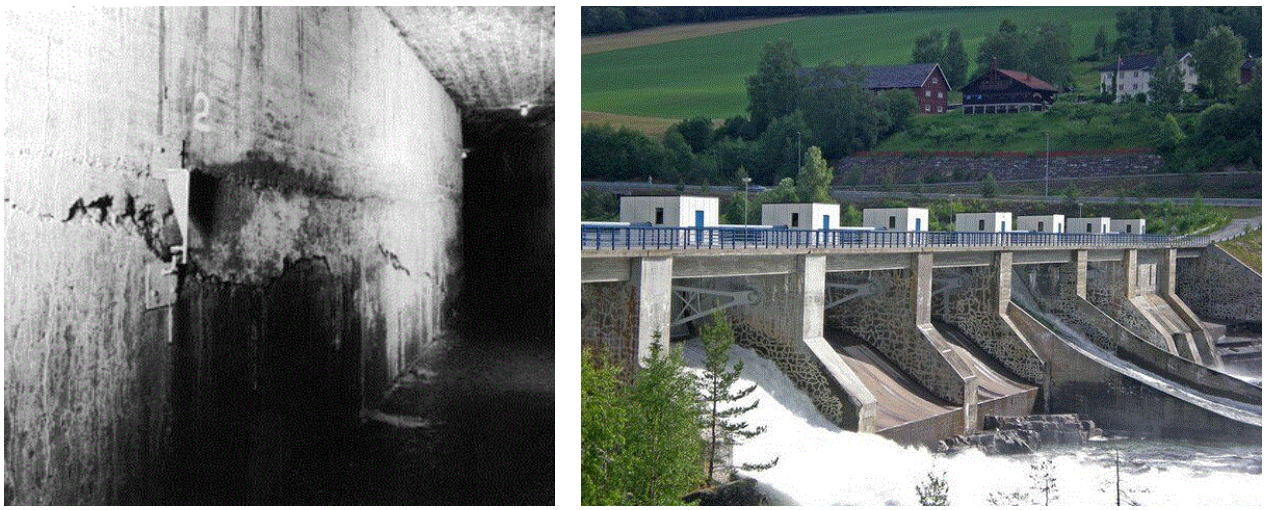


*Figure 4. Example of crack pattern due to alkali-silica reaction: Fontana dam (inspection galley by Ingraffea, 1990); dam in Norway by Thomas et al., 2013.*

About buttress and slab/arch dams, in Italy there are 1 slab dam, 8 multiple arch dams, 13 buttress dams and 15 hollow gravity dams, all of them built in the last century (Figure 5). For this reason, some rehabilitation works have been required to respect the new regulations and guarantee their safe operation over time.

The Italian Committee on Large Dams (ITCOLD) has set up the Working Group "Behaviour, problems, rehabilitation of hollow gravity, buttress and multiple arch/slab dams", whose main topics refers to control and monitoring systems, criteria for safety assessment, rehabilitation works. Several case histories have been analysed by this Working Group: e.g., Ancipa dam (a hollow gravity infrastructure, located in Sicily and operated by ENEL Green Power), in which a steel insulating shield was built on the downstream face to reduce the seasonal thermal gradients and slow down the propagation of cracks in the buttresses; San Giacomo di Fraele dam (a buttress infrastructure, located in Lombardy and operated by A2A), for which the partial closure of the buttresses with a sloped slab was created to reduce the effects of a reservoir located downstream the dam, thus prevent sliding (Figure 6).

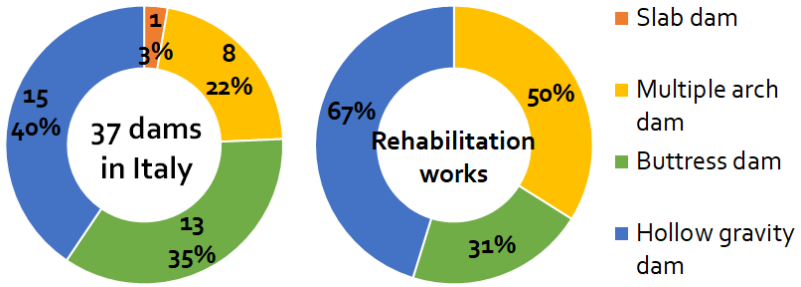



*Figure 5. Number of dams belonging to slab/multiple arch, buttress and hollow gravity dams in Italy and percentage of structures that underwent rehabilitation works according to their type.*

*Figure 6. Ancipa dam: construction of the steel insulating shield on the downstream face (left). San Giacomo di Fraele dam: weighting of the downstream lower part (right).*

## 3. The importance of numerical modeling

For assessing the safety of strategic hydraulic structures (e.g., dams) and understanding the influence of several impact phenomena (temperature, humidity, degradation of materials), numerical modelling, in which different loading conditions and possible crack patterns are implemented, plays a fundamental role.

Advanced numerical modelling (e.g., finite element models, FEM) can help to remove the conservative assumptions of simple approaches and to describe with greater accuracy the real behaviour of dams. Thus, operating restrictions that directly impact on the clean energy production of these power plants and their storage capacity can be prevented, in such a way to respect the European Union energy and climate targets.

Indeed, hydroelectric power plants are essential in the transition towards a decarbonized energy system, thanks to their capacity for delivering balancing services to the power network. Furthermore, the effects of long periods of drought or flooding can be mitigated thanks to the storage capacity of dams preventing catastrophes for agriculture and society at large. Finally, numerical modelling can be used for diagnosis of possible damage in aged structures as well as to support design engineers in the choice of the most effective rehabilitation solution for keeping the structures in safety conditions over time.

## 4. Case history of Molato dam (Italy)

Molato dam, operated by the *Consorzio di Bonifica di Piacenza*, blocks Tidone River in Emilia-Romagna (Italy) and provides water for irrigation with its total storage capacity of 13 $Mm^3$. It is a reinforced concrete multiple arch and buttress dam (Figure 7), built between 1921 and 1928, with two gravity lateral abutments, 55 m high and a crest length of 335 m.

The dam consists in 17 reinforced concrete arches, inclined 45° to the horizontal plane, resting upon intermediate buttresses, which are 10 m apart (connected by reinforced concrete T-shape beams in the transversal direction, Figure 8) and have a variable thickness from 2.40 m at the base to 0.90 m at the top (ANIDEL, 1953). The arches have a circular section with a constant extrados radius of 5 m and a thickness which originally varied from 1.20 m at the base to 0.45 m at the top. In the 80s all the arches were thickened up to 2.40 m at the base e 0.90 m at the top.

At the base of the arches and the buttresses a concrete slab which covers and protects the rock foundation has been built in the period 2002-2005.

In the central part of the dam, there is a concrete spillway consisting of three sluices 8.80 m wide, controlled by automatic balance sector gates.

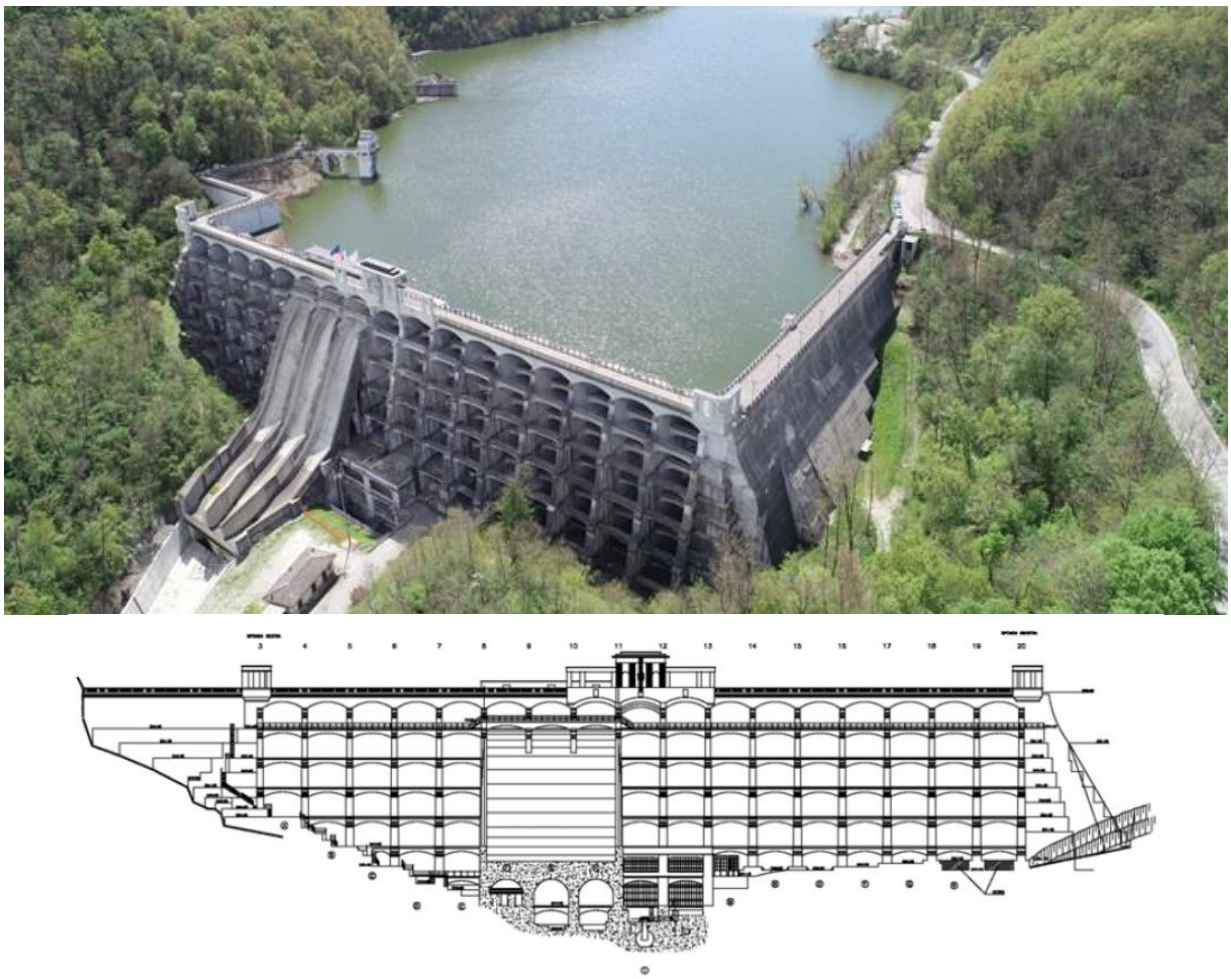


*Figure 7. Downstream face views of Molato dam.*

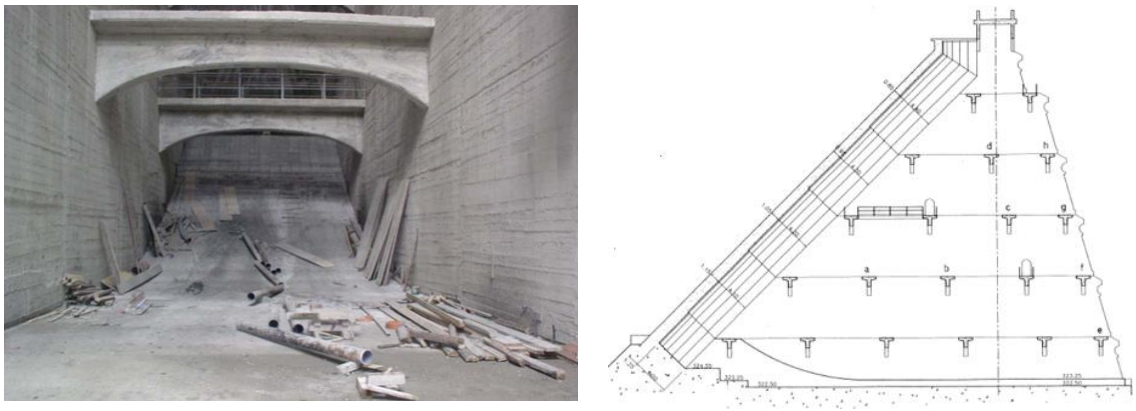


*Figure 8. Reinforced concrete T-shape beams, connecting dam buttresses.*

### 4.1. Finite element model

The seismic response of Molato dam was evaluated, according to Italian standard (DM2014; DM2018), by means of a numerical model capable of taking into account both the non-linear behaviour of the concrete and the dam-rock foundation interface.

The finite element model (Figure 9), used in the seismic reassessment of Molato dam, consists of solid elements for buttresses, slabs, concrete weightings among spans, gravity shoulders and rock foundation; beam elements for the T-shaped beams; shell elements for the multiple arches; acoustic elements for the reservoir (the mesh of the reservoir domain was obtained by extruding the dam upstream face over a length three times the dam height and was connected only with the upstream dam elements).

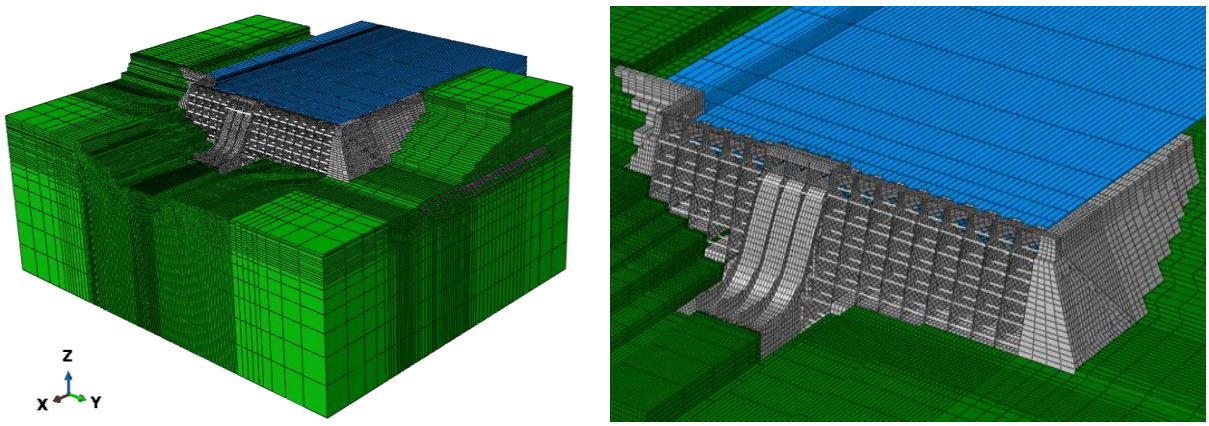



*Figure 9. Finite element model of the dam-rock-reservoir system.*

A Mohr-Coulomb frictional model was assigned to the dam-rock foundation interface. A shell to solid coupling interaction was adopted to join shell elements to solid.

The nonlinear concrete behaviour was simulated using an elasto-plastic damage constitutive model (Lee & Fenves, 1988), while for the rock foundation a linear elastic behaviour was assumed.

The dynamic fluid-structure interaction was modelled according to the classic approach of the mechanical-acoustic coupling suggested by Zienkiewicz, 1977. The acoustic approach allows to consider both the compressibility of water and the damping effects at the boundary of the fluid domain.

The traditional massless approach (Clough, 1980), in which rock foundation is assumed without mass, was adopted. This method is somewhat conservative because it does not take into account the energy dissipated in the rock foundation during the seismic motion.

### 4.2. Seismic analyses

The seismic structural response of Molato dam was evaluated performing time history analyses and applying the following forces: gravity load, hydrostatic pressure and corresponding uplift (for three different water level conditions: maximum level of regulation, intermediate level and empty reservoir), winter thermal load (which represents the worst condition) and seismic forces.

The seismic actions for the various limit states (serviceability and the ultimate limit states, according to DM2014) were defined starting from the "basic seismic hazard" of the site where the dam is located. Natural accelerogram terns were chosen: in Figure 10 the upstream-downstream (X), shoulder-to-shoulder (Y) and vertical direction (Z) of the accelerogram tern called SADR is shown.

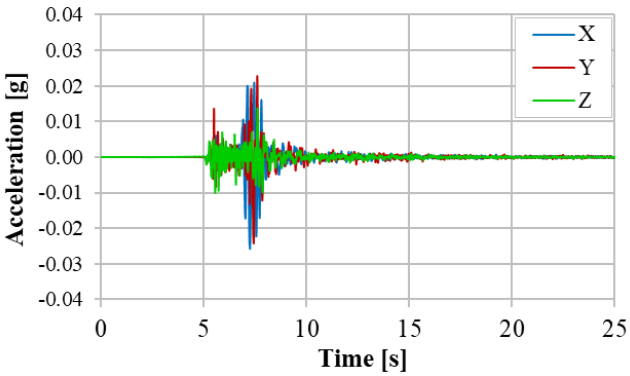



*Figure 10. The accelerogram tern called SADR.*

According to the analysis type and the structural elements, different criterions were followed.

Referring to the stress state, according to US Army Corps of Engineers (USACE, 2007), in arch structures the following parameters have to be controlled: the maximum principal stresses can be up to twice the tensile strength of concrete (equal to 1.8 MPa), but only up to a fifth of the total area of the upstream and downstream face and for a cumulative duration not exceeding 0.4 s (Figure 11).

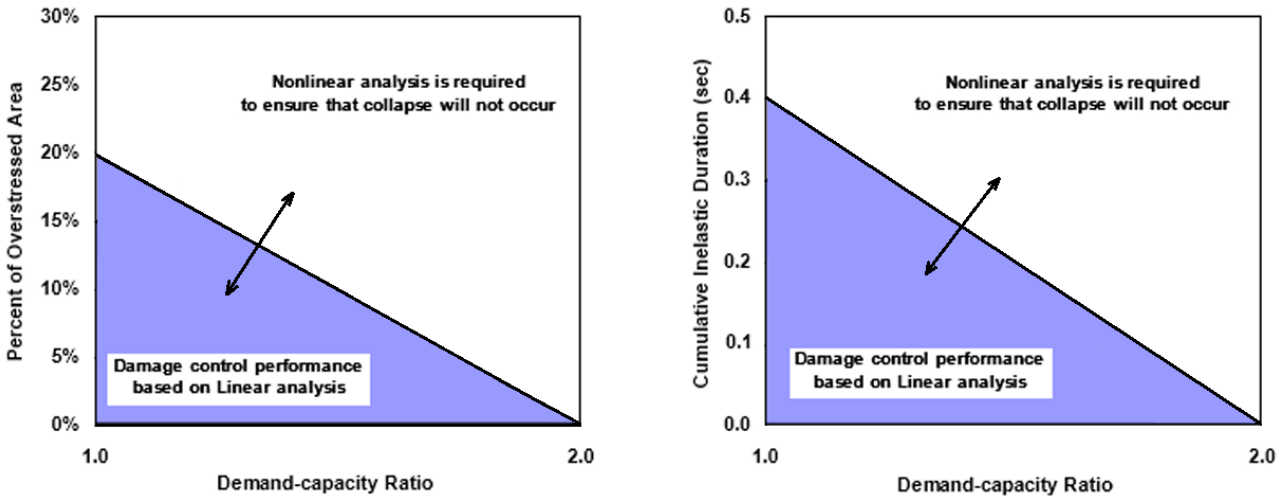



*Figure 11. Prescription about seismic analyses in arch dam, according to USACE, 2007.*

Considering the accelerogram tern called SADR (Fig. 10), in Figure 12 the maximum principal stresses envelop on the upstream face, obtained considering the maximum level of reservoir, is shown. This parameter does not overcome the tensile limit defined according to USACE (3.6 MPa) in all the multiple arches.

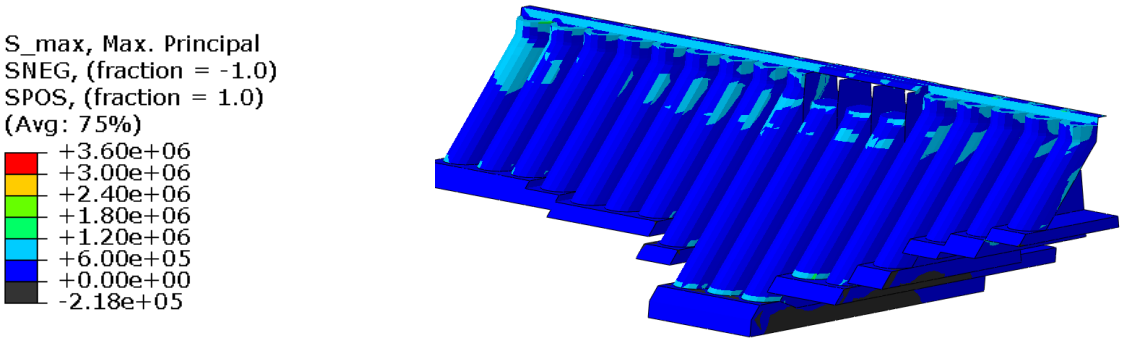



*Figure 12. Maximum principal stresses envelop on the upstream face with the maximum level of reservoir.*

For the buttresses and the shoulders, considered equivalent to gravity dams, sliding stability must be checked in all the horizontal sections (joints and dam-rock foundation interface, Figure 13 left). The verification is satisfied if for each section the ratio between the sum of horizontal forces ($F_x$) and the sum of vertical forces ($F_y$) is less than one. The most stressed buttress was considered (Figure 13, right) and the forces acting, when the maximum seismic acceleration is present, were evaluated.

Table 1 shows that the safety against sliding is satisfied in all horizontal sections for the acceleration tern SADR with the maximum level of reservoir.

*Table 1. Sliding safety verification for the acceleration tern SADR with the maximum level of reservoir.*

| Section | $F_x$ [kN] | $F_y$ [kN] | $F_x$ / $F_y$ [-] |
|---|---|---|---|
| A | 47 | 4660 | 0.010 |
| B | 1540 | 9050 | 0.170 |
| C | 11300 | 35700 | 0.317 |
| D | 18000 | 46900 | 0.384 |

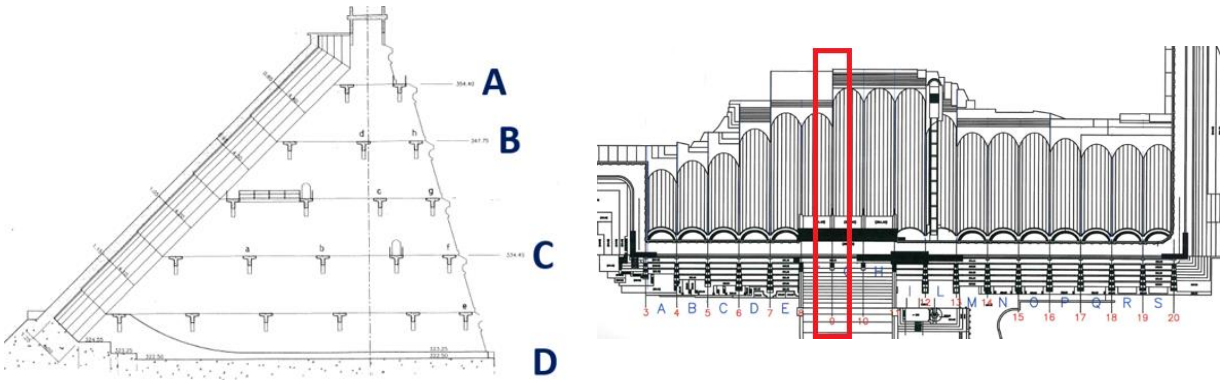



*Figure 13. Horizontal sections and the most stressed buttress considered for the sliding safety.*

For the reinforced concrete T-shaped beams and arches, starting from the geometrical and mechanical parameters of the section, a bending moment versus axial force diagram was computed to define the strength domain. A reinforced cross-section is verified if the acting bending moments and axial forces are inside this domain at any time step of the analysis. Results for the acceleration tern SADR and the maximum level of reservoir are reported in Figure 14: the comparison between the strength domain and the acting force couples (bending moment versus axial force) for the most stressed T-shaped beam (above) and arch (below) is shown. Four different acting force couples are reported: static loading condition in purple; maximum tension and compression over the seismic analysis, respectively in light blue (only for the T-shaped beam) and pink; final condition in yellow. The analyses are satisfied since the acting forces are inside the strength domains.

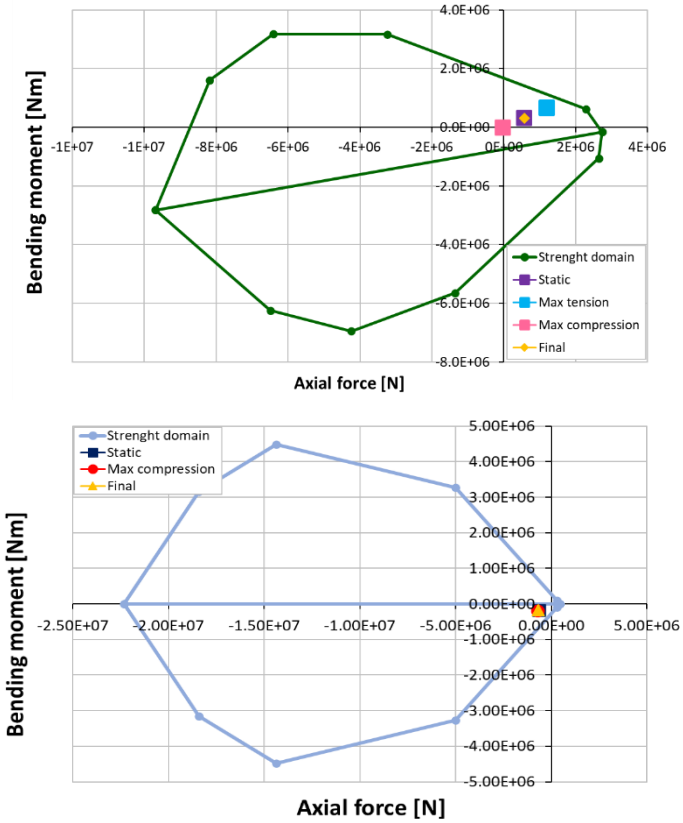



*Figure 14. Bending moment versus axial force diagram for the most stressed T-shape beam (above) and arch (below) for SADR tern and maximum level of reservoir.*

## 5. Conclusion

In this paper an overview of the typical problems concerning buttress, hollow gravity and multiple arch/slab dams has been provided.

Then, the role of numerical modeling has been highlighted for the evaluation of dam safety, for diagnostic investigation and for identifying the most effective rehabilitation works to guarantee long-term safety conditions.

Finally, the seismic analyses of Molato dam, operated by the *Consorzio di Bonifica di Piacenza*, is presented. This case study demonstrates how numerical analysis allows evaluating the real response of all the structural elements of a strategic dam. In conclusion, it is extremely evident that the properties of the materials, the constitutive laws, the geometric characteristics and the acting loads play a fundamental role in the evaluation of the seismic behavior of dams.

## 6. Acknowledgement

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## 7. References

ANIDEL (1953). *Dams for hydroelectric power in Italy*, Vol. 7.

Ardito R., Maier G., Massalongo G. (2008). Diagnostic analysis of concrete dams based on seasonal hydrostatic loading, *Engineering Structures*, Vol. 30: 3176-3185.

Brownjohn J.M.W. (2007). Structural health monitoring of civil infrastructure, *Philosophical Transactions of the Royal Society A*, Vol. 365: 589–622.

Bukenya P., Moyo P., Beushausen H., Oosthuizen C. (2014). Health monitoring of concrete dams: a literature review, *Journal of Civil Structural Health Monitoring*, Vol. 4: 235–244.

Clough R.W. (1980). Non-linear mechanisms in the seismic response of arch dams, *Proceedings of the International Research Conference Earthquake Engineering*, Skopje, Yugoslavia.

Colombo M., Domaneschi M., Ghisi A. (2016). Existing concrete dams: loads definition and finite element models validation, *Structural Monitoring and Maintenance*, Vol. 3: 129-144.

Colombo M., Domaneschi M., Ghisi A. (2015). Validation of Finite Element Models of concrete dams through monitoring data, *Proceedings of the 10th International Workshop on Structural Health Monitoring*, Stanford University, USA, Vol. 2: 473-480.

Evangelisti G. (1982). *Impianti idroelettrici*, Vol. I, Patron, Bologna.

Ingraffea A.R. (1990). Case studies of simulation of fracture in concrete dams, *Engineering Fracture Mechanics*, Vol. 35: 553-564.

Lee J., Fenves G.L. (1998). A plastic-damage concrete model for earthquake analysis of dams, *Earthquake Engineering and Structural Dynamics*, Vol. 27: 937-956.

Ministero delle Infrastrutture e dei Trasporti (DM2014). *Decreto Ministeriale 26 Giugno 2014. Norme tecniche per la progettazione e la costruzione degli sbarramenti di ritenuta (dighe e traverse)*.

Ministero delle Infrastrutture e dei Trasporti (DM2018). *Decreto Ministeriale 17 gennaio 2018. Norme tecniche per le costruzioni*.

Mirzabozorg H., Hariri-Ardebili M.A., Heshmati M., Seyed-Kolbadi S.M. (2014). Structural safety evaluation of Karun III Dam and calibration of its finite element model using instrumentation and site observation, *Case Studies in Structural Engineering*, Vol. 1: 6–12.

Thomas M., Folliard K.J., Fournier B., Rivard P., Drimalas T. (2013). *Methods for Evaluating and Treating ASR-Affected Structures: Results of Field Application and Demonstration Projects*, U.S. Department of Transportation.

USACE (2007). *Engineering and Design - Earthquake Design and Evaluation of Concrete Hydraulic Structures*, EM 1110-2-6053.

Zienkiewicz O.C. (1977). *The Finite Element Method*, 3rd Edition, McGraw-Hill.