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# Existing concrete dams: loads definition and finite element models validation

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**Abstract.** We present a methodology to validate with monitoring data finite element models of existing concrete dams: numerical analyses are performed to assess the structural response under the effects of seasonal loading conditions, represented by hydrostatic pressure on the upstream-downstream dam surfaces and thermal variations as recorded by a thermometers network. We show that the stiffness effect of the rock foundation and the surface degradation of concrete due to aging are crucial aspects to be accounted for a correct interpretation of the real behavior. This work summarizes some general procedures developed by this research group at Politecnico di Milano on traditional static monitoring systems and two significant case studies: a buttress gravity and an arch-gravity dam.

**Keywords:** existing concrete dams; thermal analysis; finite element model; validation; monitoring data

## 1. Introduction

As in many European and developed countries, today in Italy there are few possibilities to design and build new dams, while there is a strong need to keep existing dams in safe service conditions. Service life may induce structural deterioration, in particular when it exceeds six or seven decades. A recently introduced Italian standard is indeed focused into this aspect by suggesting the development of a reference dam model (e.g., finite element – FE – model) able to reproduce the actual structural response, as defined by the available monitoring data (D.M. 26 June 2014).

The existing dams are usually monitored through regular inspections and measurement systems, in order to promptly identify any abnormal behavior, whose reasons to appear should be carefully understood.

To define the activities and instruments which can be taken into account to supervise the "health" of an existing infrastructure, such as a dam, the "Structural Health Monitoring" (SHM) term is used (Bukenya *et al.* 2014). The SHM verifies the external actions and the structural response to these loads (i.e., slow movements of the rock close to a dam due to geological phenomena).

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The monitoring activity can be classified as static or dynamic: the first involves measurements of static factors (e.g., environmental temperature and reservoir level), while dynamic monitoring of dams is focused on the performance of dams under vibrations. Data obtained by monitoring is analyzed using statistical and/or deterministic models: statistical models usually relate the present and the past behavior of the dam (Domaneschi *et al.* 2013, 2015); deterministic models establish the relationship between the loads and the dam response, defined by a structural analysis (see Mirzabozorg *et al.* 2014).

Monitoring techniques can be classified as traditional and innovative. Among the first, pendulum, piezometers and thermometers are probably the most adopted on existing dams, as defined in Ashtankar and Chore (2015). Besides, in situations that are very sensitive to failure risk or for detecting early-stage events, innovative monitoring systems have to be implemented, such as radar equipment and fiber optic sensors. Some examples are presented in Ardito *et al.* (2008), Inaudi *et al.* (2013) and Glišić and Inaudi (2007).

Besides black-box models for monitoring data temporal series, e.g. in Palumbo and Piroddi (2001), or monitoring data statistical models, see e.g., Li *et al.* (2015), De Sortis and Paoliani (2007), Mata *et al.* (2007), the physical-mathematical model of a dam-foundation system should be considered a fundamental part of the SHM system. Under known external loads, the comparison between the FE structural response and the effective behavior of the dam (in terms of quantities defined by monitoring systems) represents a crucial element in order to understand the real phenomena.

Employing SHM, the external loads (e.g., reservoir level variations or slow movements of a dam abutments due to geological phenomena), as well as the corresponding structural response, are kept under control. To effectively match numerical results and experimental data, a model updating procedure can be assumed. In Mirzabozorg *et al.* (2014), an arch dam model is validated and subsequently used in safety verifications. Differences come from many sources, e.g. assumed boundary conditions and material properties, as shown in Bayraktar *et al.* (2011).

The stiffness distribution into the rock mass and into the dam body represents an important aspect to be taken into account for reproducing the real response of the structures. They usually are established by independent geo-mechanical investigations and laboratory tests on specimens.

Despite this information, when existing and aged dams are assessed, the effect of the micro-cracked concrete surface, due to seasonal self-equilibrated stress states during the whole life of the dam, has to be accounted in the model. A possible engineering solution consists into adopting different properties for the material on the upstream-downstream surfaces with respect to the internal bulk.

With reference to existing concrete buttress gravity and arch-gravity dam, we show a procedure for FE model preparation and validation accounting for seasonal monitoring data commonly available. Such models are usually employed to evaluate the structural response of the dams under service loads and to perform the analyses defined by the current standards (namely static, thermal and seismic analyses).

We perform numerical analyses in the two aforementioned case studies to assess the structural response under the effects of seasonal loading conditions, represented by hydrostatic pressure on the upstream-downstream dam surfaces and thermal variations in the continuum detected by the monitoring system. The effectiveness of the models is then evaluated by comparing results in terms of displacement and temperatures with corresponding monitoring data, while the effects exerted by the self-weight of the concrete structures are disregarded, since they are already included at the installation of instruments and sensors. In the next Section 2 we explain the whole procedure, then in Sections 3-8 the single steps are shown more in deep. Conclusions are finally drawn in Section 9.

## 2. Ratio of the procedure

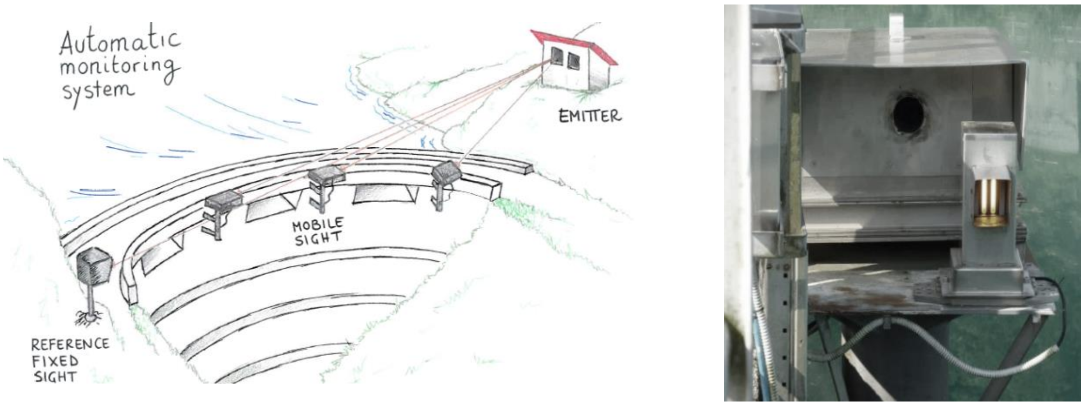
We propose a methodology to validate finite element models based on data commonly available during (large) dam monitoring. We assume that dam geometry requires, because of its actual complexity or its relevance (e.g., to assure life protection in populous zones with state-of-the-art analysis), a three dimensional, continuum model. The methodology can then be adopted for different dam typologies and in this work we show its application to a gravity buttress dam with uncommon characteristics and to an arch-gravity dam. From a logical point of view, the approach consists in the following steps.

1. Collect seasonal monitoring data for the reservoir water level and daily temperatures during several service years. Temperatures should be measured both for air, water and in the dam bulk, more precisely in the neighboring of the external surface (in particular the wet surface), in the walkways internal to the dam (if any), and in the rock foundation.
2. From the data in step 1, extract a seasonal, periodic (e.g., sinusoidal) behavior for water level and thermal boundary conditions for a “reference year”. Differences from the reference year should be treated apart; actually, the procedure should aim to evidence abnormal behaviors.
3. Build a three-dimensional finite element model of the dam-foundation system, accounting for the reservoir geometry, in particular the bathymetry near the dam wet surface.
4. Execute a three-dimensional thermal analysis of the dam subjected to boundary conditions as defined at step 2 and check the model consistency through the comparison of temperature time evolution at internal points between numerical results and monitored values.
5. Calculate, for each point (actually for each mesh node), the thermal increase or decrease with respect to the pointwise mean value for the reference year.
6. Execute a three-dimensional structural analysis of the dam subjected to the hydrostatic load, varying according to the reference year, and to the pointwise thermal loads obtained at steps 2 and 5, respectively. Compare the displacements at the crown or at other significant points with the monitored displacements.

After the model has been validated, other load conditions such as exceptional water level excursions, e.g., due to maintenance, or special temperature changes, can be controlled as well, in order to exclude that irreversible effects would arise due to exceptional circumstances. Finally, the model is ready for the analyses with any load condition, e.g., seismic analysis.

## 3. Traditional monitoring instruments

Dams are engineering structures with a high potential risk related to the presence of the reservoir. The monitoring system has to assess that the dam behaves as expected, e.g., within the safety level defined by the designer and approved by the supervising agency.



(a) Arch-gravity dam (b) Collimator

Fig. 1 Monitoring schemes

The SHM system, the inspection methods and data processing must have specific basic requirements: consistency between the geometric density and the time frequency of observations; capability to simultaneously perform analyses processes and comparisons with observations; minimum time between measures and information processing.

Observing a dam behavior, it is possible to distinguish between external actions (inducing changes in the dam) and response quantities (structural response to the variations of the cause quantities). The main external actions are the reservoir level, the temperature changing (in the air, water and concrete domain), precipitations (rain and snow), weather conditions (humidity, pressure and wind), the ice thickness, the reservoir bathymetry and seismic events. The response quantities are, instead, local deformations, stresses, horizontal and vertical displacements (absolute and relative), joint displacements and cracks, uplift and pore pressure, changes in physical-mechanical characteristics of the materials.

Both external and response quantities are subjected to continuous time variations, which have to be monitored in order to define the agreement between the measured response quantities and the computational counterparts.

The definition and the installation of a monitoring system depend actually on the dam type (arch, gravity or buttress), materials, service life, dimensions, reservoir capacity and risk related to the downstream population density. Figs. 1(a) and 1(b) reports a typical monitoring scheme for an arch-gravity dam and a collimator.

In the studied cases, monitoring data of thermometers (manual and automatic) and of inverted plumb line are considered for validating the FE models: they consist respectively in temperatures and upstream-downstream displacements. In Figs. 2(a) and 2(b) the positions of the inverted plumb lines for each studied dam are depicted.

## 4. Seasonal loading conditions

In this work the validation of the FE models is conducted by exploiting quasi-static seasonal loadings, represented by hydrostatic and thermal actions registered for several years. The FE models are tuned with the goal to minimize the discrepancy between the numerical results and the corresponding measured quantities. The effects of dead load, in terms of displacements, are assumed being absorbed by the dam prior to the installation of the monitoring system, and, therefore, they are herein disregarded.

### *4.1 Temperature variations*

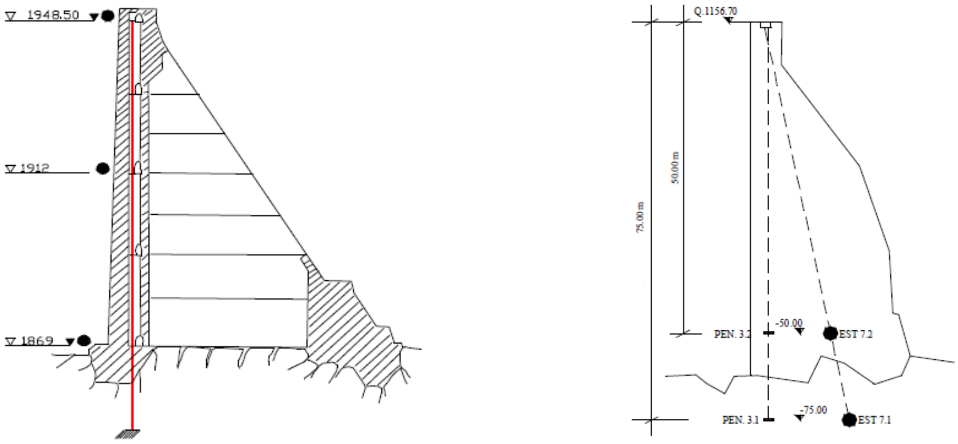
Heat transmission into the dam body is typically conductive and can be modeled through a standard thermal FE analysis. It is easy to impose the boundary conditions when the temperatures can be assumed as given along the whole surface which bounds the domain of the thermal analysis. This is the case when a thermometers network, placed at a depth of some centimeters from the external surface, is present (see Fig. 3 for the central buttress of the gravity dam considered), as for the dams studied in this work. Otherwise, radiation and convention boundary conditions should be applied.

Sinusoidal functions, such as shown in the following Eq. (1), have been used to approximate the periodic variation of temperatures on the dam surface

$$T = T_{average} + A\sin(\omega t + \varphi) \tag{1}$$

where:
$T=T(x,t)$ is the temperature of the point x at time t;
$T_{average}=T_{average}(x)$ is the average temperature in the year;
$A=A(x)$ in the sinusoidal amplitude;
$\omega$ is the circular frequency;
$\varphi$ is the sinusoide phase.

Fig. 4 reports an example of the temperature measured by an automatic thermometer and of the corresponding approximating function, while Fig. 5 shows the applied boundary conditions for the thermal analysis.



(a) Gravity buttress dam (b) Arch-gravity dam

Fig. 2 Dispositions of inverted plumb lines

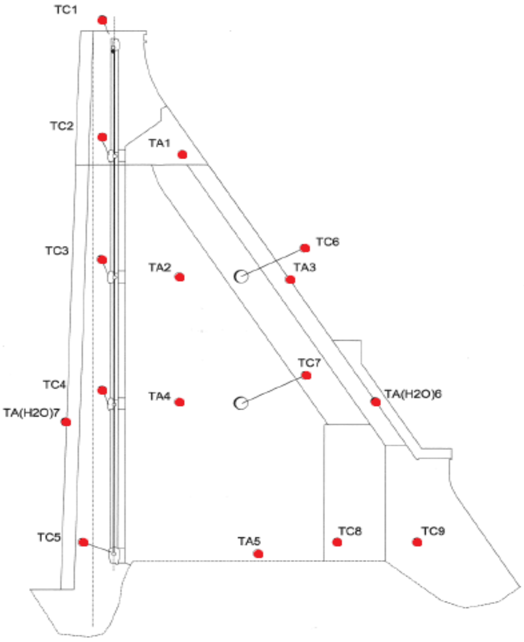


Fig. 3 Example of thermometer network placing in the central section of the buttress dam. Legend: TA stands for air temperature, while TC refers to concrete temperature

It is worthwhile to emphasize that in the monitored points the temperature boundary condition at the wet surface is assumed to vary linearly in space and as a sinusoid in time, as indicated in Fig. 5. For the dam surfaces into contact with air, rock foundation and inside the hole, created downstream by the strengthening structure superimposed to the dam (we clarify later in Section 5 the peculiarities of the considered gravity buttress dam), the value measured at the monitoring point is applied constant.

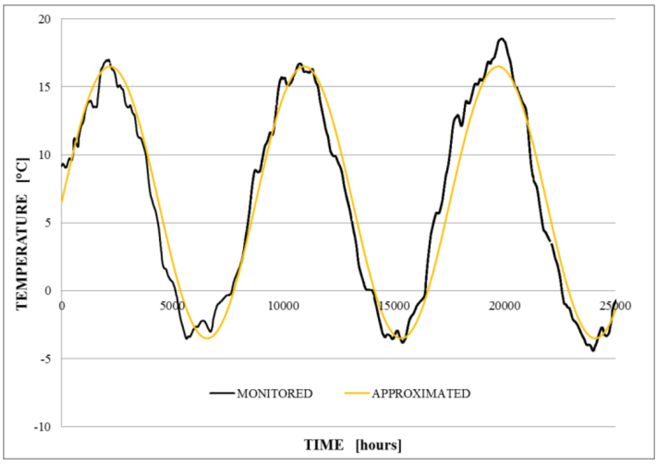
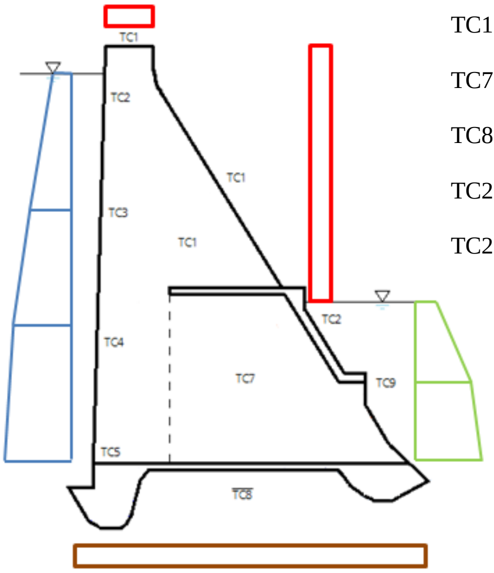


Fig. 4 Temperature recorded by an automatic thermometer and corresponding approximating function

### *4.2 Hydrostatic loading*

The reservoir level variation can be also considered periodic. For one of the dams studied in this work, Fig. 6 gives the monitored water level (in terms of meters above sea level) for various years and the approximating function, chosen to represent the typical average annual variation. Note that the minimum water level occurs in spring (day 0 is at the beginning of the solar year), while the maximum is in autumn.

It is worth underlying that temperature time histories on the dam upstream surface depend on the evolution of the reservoir level; therefore, during the subsequent structural analysis the time variations of both the seasonal loads (thermal and hydrostatic) have to be taken into account.



TC1 = air temperature

TC7 = hole temperature

TC8 = ground temperature

TC2, TC3, TC4, TC5 = upstream water temperature (variable linearly)

TC2, TC9 = downstream water temperature (variable linearly)

Fig. 5 Boundary conditions in terms of temperature for the gravity buttress dam

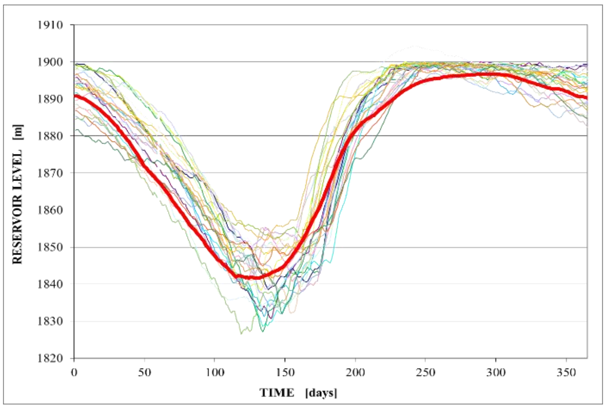


Fig. 6 Reservoir level and corresponding approximating function, with t=0 representing the 1st January

## 5. Solid and finite element model of dam-foundation system

In this step we create the geometric solid model of the dam-foundation system and then its finite element approximation. In the following, large concrete dams of two different types are considered: a gravity buttress dam with uncommon features and an arch-gravity dam.

For the first, the FE discretization and the subsequent analyses are performed for a significant portion of the dam-foundation system, representative of the dam central slice, constituted by the two maximum height buttresses (see Fig. 7), with the corresponding rock foundation. The surfaces which bounds this portion are considered flat and without friction and they are fixed in buttresses direction in terms of displacements. The dam has been modified about ten years ago with the addition of a concrete slab closing the downstream open space between buttresses at the lower height, depicted in green color in the electronic version of Fig. 7. Moreover, a layer of spritzed concrete has been added to the downstream surface. The reasoning was to increase the dam weight to improve its translational stability and to recreate a (sub-)vertical wet surface for the downstream basin. The dam actually separates two reservoirs, the lowest one created by another dam at lowest altitude.

Fig. 8 depicts, instead, the solid models belonging to the arch-gravity dam, defined, as for the gravity buttress dam, through the original design drawings.

With regard to the rock foundation, the surface topography has to be described within the models. For this purpose, the available data can be collected from various sources, such as topographic regional maps and reservoir surveys. Figs. 9 and 10 depict an example of the details for the buttress dam.

The size of the rock foundation region, to be included in the model, can be defined according to USACE (2003), and therefore it is prudentially set equal to three times the maximum dam dimension in each global direction. It is demonstrated that further extensions of the domain of interest would not produce significant changes in the system response in terms of stresses and strains for the typical dam loading conditions. Fig. 11 shows an example of a complete dam-foundation solid model for an arch-gravity dam. Finally, complete dam-foundation FE models of the considered arch-gravity and buttress dams are depicted in Figs. 12(a) and 12(b).

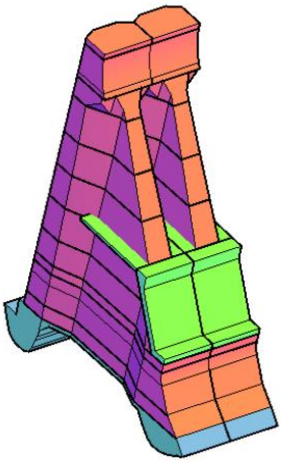


Fig. 7 Solid model of the central part of the gravity buttress dam

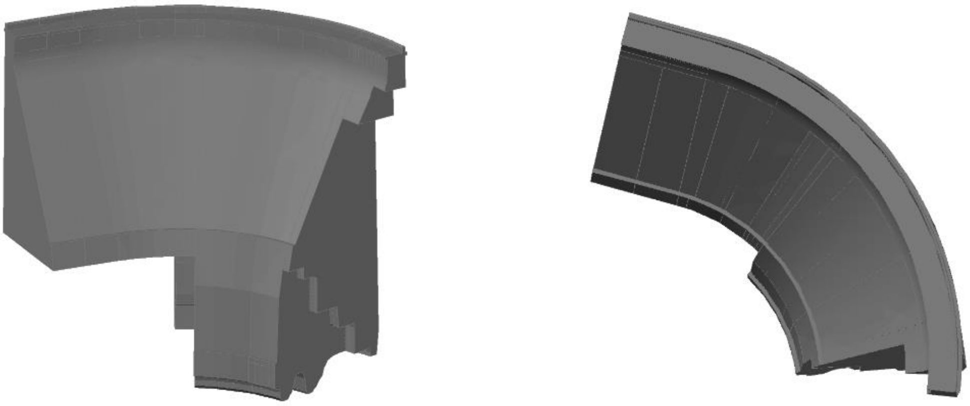


Fig. 8 Solid models of arch-gravity dams

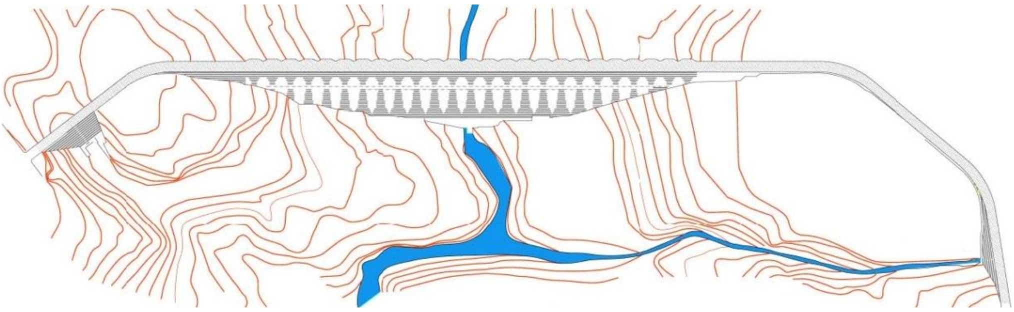


Fig. 9 Reservoir map (downstream) for the gravity buttress dam

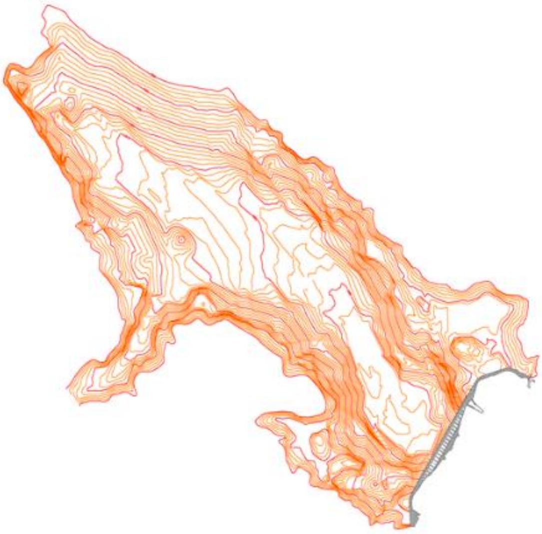


Fig. 10 Reservoir map (upstream) for the gravity buttress dam

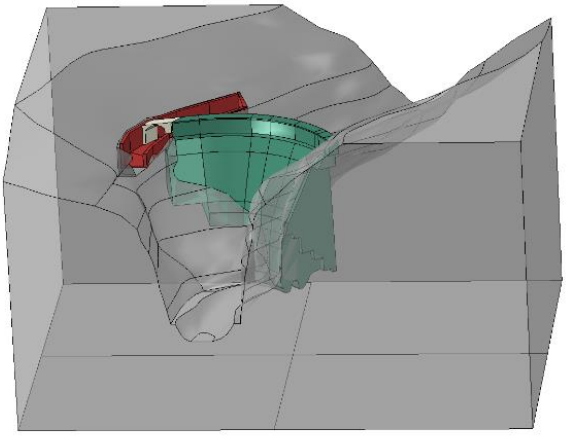


Fig. 11 Complete dam-foundation solid model for arch-gravity dam

## 6. Thermal analysis of the dam

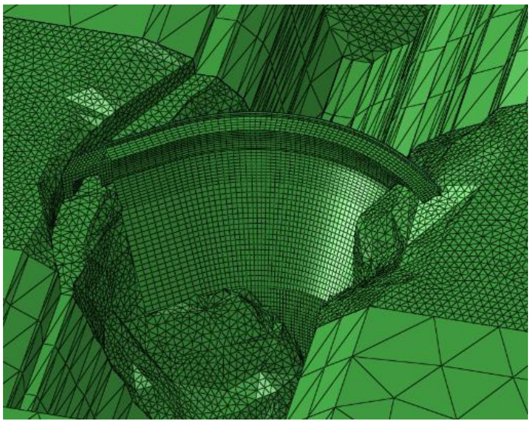
The study of the thermal phenomena which occur in a dam and the effects (displacements, strains and stresses) produced by temperature variations, can be evaluated by an elasto-thermal analysis and represents a topic of theoretical and practical interest, see e.g., Sheibany and Ghaemian (2006).

However, we simplify the approach, by decoupling the thermal from the mechanical regime, and we execute in sequence first a three dimensional, transient thermal analysis, which defines the stabilized annual thermal cycle for a dam, and then we carry out an elastic static analysis, reported in the following Section 7, where the effects in terms of stresses and displacements due to the thermal deformations are finally obtained.

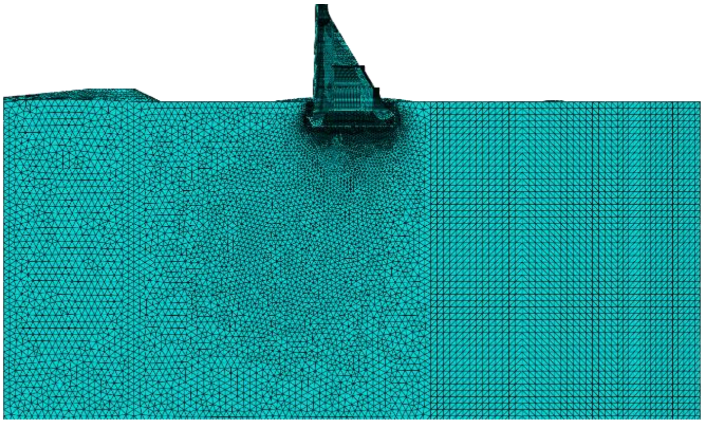
The thermal boundary conditions can be usually considered cyclically repeated every year, due to the hydropower service of the structure.

In existing dams, with a service life of decades, concrete shrinkage and heating phenomena, generated by the concrete hydration, are considered completed. Consequently, the associated residual stresses can be disregarded owing to concrete viscosity. On the contrary, it is important to assess the stress state induced by temperature changes, occurring in a dam due to environmental changes. In the following we exclude effects arising from alkali-silica reactions (AAR) in the concrete bulk, see Comi *et al.* (2009), since they have not been significantly developed in the considered dams.

Léger and Leclerc (2007) evaluated the solution for the heat conduction in a wall, on the sides of which sinusoidal temperatures are imposed. However, in order to consider the heat transmission by conduction through a more general approach, with complex three dimensional geometries it is possible to impose boundary conditions in terms of temperature on the dam external surface as collected by monitoring instrumentation. This methodology has been applied to the selected case studies and it appears well sound when the instrumentation available data reports the temperature in the neighboring of the dam surface.



(a) Arch-gravity dam



(b) Central block of a buttress dam

Fig. 12 FE models of dams, including foundations

The study of the heat transmission by conduction is carried out through the classical Fourier equation in Eq. (2), which in a tridimensional case is defined as in Rahimi and Noorzaei (2011)

$$k \cdot \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) - \rho \cdot c \cdot \frac{\partial T}{\partial t} + Q = 0 \tag{2}$$

where:
$k$ is the thermal conductivity [J/ms °C];
$c$ is the specific heat [J/kg °C];
$\rho$ is the density [kg/m$^3$];
$Q$ is the (eventual) heat source within the dam [J/m$^3$s].

Exploiting boundary conditions in terms of temperature, a transient thermal analysis is carried out to evaluate the temperature field within the dam (in a stabilized cycle). It is performed by imposing a suitable initial condition in terms of temperature in the interior nodes (e.g., the annual average value in each point, as depicted in Fig. 13), assumed also as reference temperature for the evaluation of the thermal strains. This represents the first step of the thermal analysis, corresponding to a stationary step. Then, a second, transient in time, step is developed. The temperature variation $\Delta T(x,t)$ is finally defined as the difference between the transient analysis results at each node of the mesh and the corresponding average value.

The calculated temperature in the interior nodes, different from the position where the thermometers are placed, is staggered with respect to the external ones, as depicted in Fig. 13 for this reason, it is possible to obtain high stresses variation along the horizontal sections (upstream-downstream).

The temperature variations induce thermal strains within the dam body, defined by

$$\varepsilon_{ij}^{term}(x,t) = \alpha \Delta T(x,t)\, \delta_{ij} \tag{3}$$

where α is the thermal dilation coefficient and $\delta_{ij}$ is the Kronecker's delta.

The evaluated thermal strains are then used as input in the elastic mechanical analyses (see Section 7), and they define with the other loading conditions the stress state configuration. Temperature time histories in the positions corresponding to the monitoring thermometers are gathered and controlled.

## 7. Structural analysis of the dam-foundation system

The water level history for the reference year (see Fig. 6 as reference example) is used as input for the hydrostatic load at the dam wet surface; moreover, at each node the thermal strains defined by Eq. (3) are imposed. Note that these load conditions vary at the same time, one influencing the other.

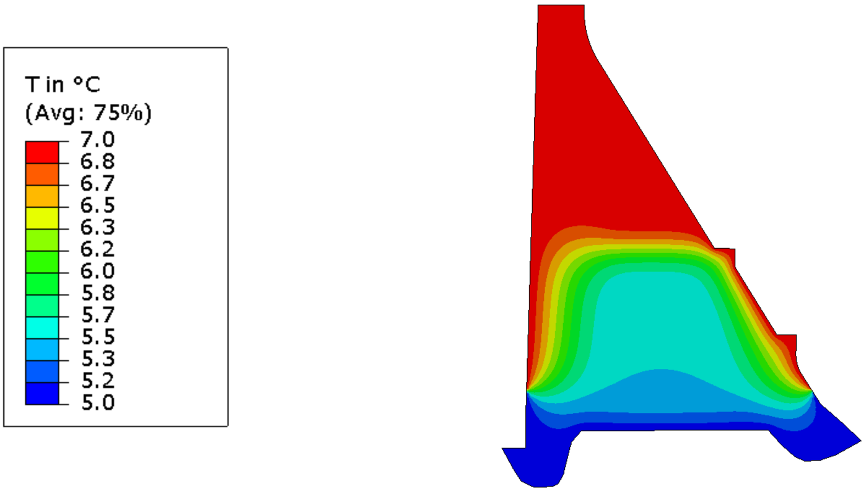


Fig. 13 Annual average value of temperature, used as input in the stationary step at the central buttress mid-section

Fig. 14 Elastic modulus distribution in the arch-gravity dam (original value in green; reduced value in red)

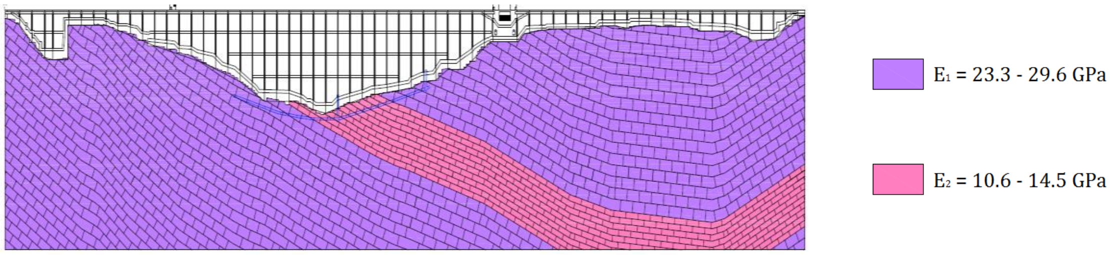


Fig. 15 Rock foundation characterization for the buttress dam

It is also important to emphasize that the stiffness distribution in the rock foundation and in the dam body represents a crucial aspect to be taken into account in order to reproduce the real structural response. They are defined by geo-mechanical investigations and laboratory tests on selected specimens, respectively. As an example, if a zone of the downstream surface turns out to be affected by extensive micro-cracking, it is reasonable to assign to such zone a reduced elasticity modulus with respect to the value used for the core concrete (see Fig. 14, in which the thickness of degradation area is about two meters, D.M. 14 January 2008). According to the analyses carried out, such damage could be caused by seasonal thermal self-equilibrated stresses.

Furthermore, with regard to the rock foundation, an elastic, piecewise-homogeneous and isotropic/orthotropic constitutive model is usually assumed as a first approximation, with different material properties obtained by a geo-mechanical survey (Fig. 15).

## 8. Comparison between FE results and monitoring data

The validation can be developed in terms of:

- temperature, by comparing the temperature of interior nodes of the FE models and the corresponding monitoring data by thermometers network, after step 3 in the sequence described at Section 2;

- displacements, by making a comparison between the displacement response of the FE model under the effects of seasonal loads with corresponding monitoring displacement measurements, step 6 in the sequence described at Section 2.

Figs. 16 and 17 show a good correspondence, respectively in terms of temperature and crest displacement (upstream-downstream direction), between the monitoring and the FE outcomes. In Fig. 17 the temperature is checked in an internal point of the gravity buttress dam (point N4 in Fig. 15). Small discrepancies are obviously present since the numerical results derive from the reference year thermal analysis and they are compared with one actual seasonal variation. For the same reason in Fig. 18 the numerical and monitored crown displacements (upstream-downstream direction) for the gravity buttress dam differ sometimes more significantly, because variations of the water level(s) from the reference year are present in the monitoring data.

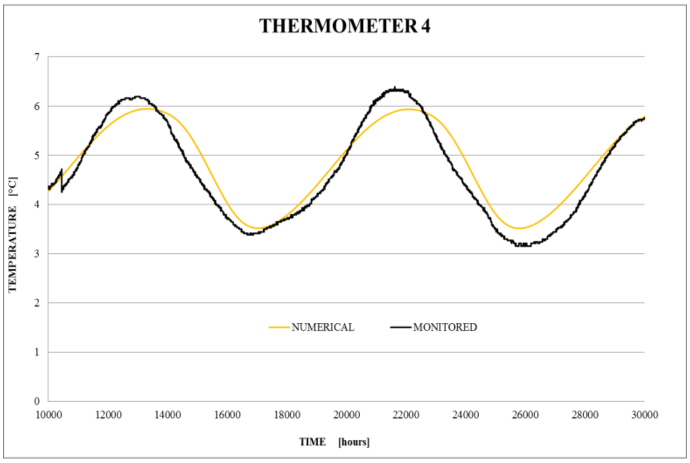


Fig. 16 Comparison between monitoring data (temperature by thermometers) and numerical results for the gravity buttress dam

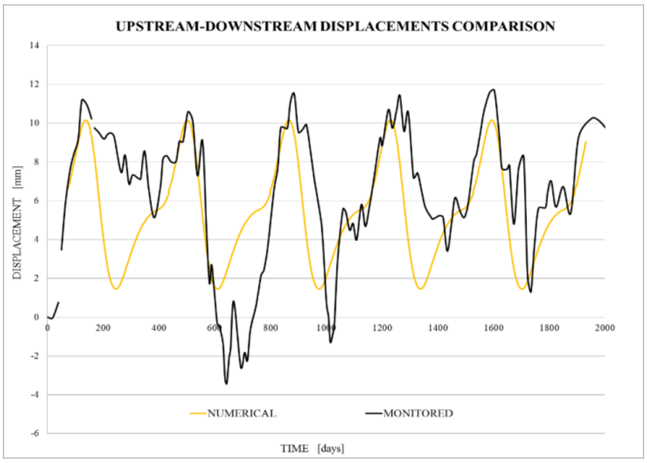


Fig. 17 Comparison between monitoring data (upstream-downstream displacements) and numerical results for the gravity buttress dam

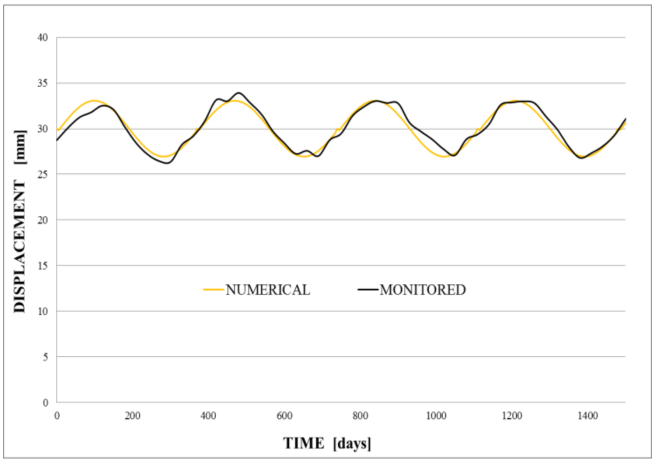


Fig. 18 Comparison between monitoring data (upstream-downstream displacements) and numerical results for the arch-gravity dam

The considered gravity buttress dam, in fact, in the recent years has been interested by a maintenance intervention, therefore the reference year load condition is built through more spread water level variations. We think that, even in this demanding case, the approach can provide a result quality ranging from acceptable to good. When, instead, the monitoring data show more regularity, as in the case of the arch-gravity dam, the comparison in terms of the relevant displacement time history is quite good, as shown in Fig. 18.

## 9. Conclusions

The structural assessment of existing concrete dams is nowadays regulated by standards requirements, where the use of numerical models, such as the finite element ones, is commonly suggested. However, this numerical approach and the related models require to be validated: the simulated structural response has to be in good agreement with corresponding monitoring data.

This work summarizes some general approaches and validation procedures, based on quasi-static seasonal loadings, for finite element models, which have been developed by the research group at Politecnico di Milano. In this work, existing large concrete dams of two different typologies are used to exemplify the approach.

The assumption of a typical annual loading cycle, in terms of hydrostatic and thermal loads, has been adopted, since this condition reflects in a fairly realistic way the actual history of external actions for the dams herein considered.

The values of the elastic modulus to be assigned to the various portions of the dam-foundation model can be calibrated through the described validation procedure.

The proposed approach demonstrates able to reproduce the actual dam behavior under seasonal thermal loading conditions and hydrostatic load, allowing to validate complex finite element models of different structural typologies, useful for further analyses as seismic ones and dam response assessment.

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## References

Ardito, R., Maier, G. and Massalongo, G. (2008), “Diagnostic analysis of concrete dams based on seasonal hydrostatic loading”, *Eng. Struct.*, **30**(11), 3176-3185.

Ashtankar, V.B. and Chore, H.S. (2015), “Thermo-structural monitoring of RCC dam in India through instrumentation”, *Struct. Monit. Maint.*, **2**(2), 95-113.

Bayraktar, A., Sevim, B. and Can Altunisik, A. (2011), “Finite element model updating effects on nonlinear seismic response of arch dam–reservoir–foundation systems”, *Finite Elem. Anal. Des.*, **47**, 85-97.

Bukenya, P., Moyo, P., Beushausen, H. and Oosthuizen, C. (2014), “Health monitoring of concrete dams: a literature review”, *J. Civil. Struct. Health Monit.*, **4**(4), 235-244.

Comi, C., Fedele, R. and Perego, U. (2009), “A chemo-thermo-damage model for the analysis of concrete dams affected by alkali-silica reaction”, *Mech. Mater.*, **41**(3), 210-230.

De Sortis, A. and Paoliani, P. (2007), “Statistical analysis and structural identification in concrete dam monitoring”, *Eng. Struct.*, **29** (1), 110-120.

D.M. 26 June 2014 (2014), *Norme tecniche per la progettazione e la costruzione degli sbarramenti di ritenuta (dighe e traverse)* – Technical Design Standard for Dams, Italy.

D.M. 14 January 2008 (2008), *Norme tecniche per le costruzioni* – General Technical Design Standard for Constractions, Italy.

Domaneschi, M., Limongelli, M.P. and Martinelli, L. (2013), “Vibration based damage localization using MEMS on a suspension bridge model”, *Smart Struct. Syst.*, **12**(6), 679-694.

Domaneschi, M., Limongelli, M.P. and Martinelli, L. (2015), “Damage detection and localization on a benchmark cable-stayed bridge”, *Earthq. Struct.*, **8**(5), 1113-1126.

Glišić, B. and Inaudi, D. (2007), *Fibre Optic Methods for Structural Health Monitoring*, John Wiley & Sons, Lugano, Swizterland.

Inaudi, D., Cottone, I. and Figini, A. (2013), “Monitoring dams and levees with distributed fiber optic sensing”, *Proceedings of the 6th International Conference of Structural Health Monitoring Intelligent Infrastructructure*, Hong Kong.

Léger, P. and Leclerc, M. (2007), “Hydrostatic, Temperature, Time-Displacement Model for Concrete Dams”, *J. Eng. Mech.-ASCE*, **133**(3), 267-277.

Li, F., Wang, Z., Liu, G., Fu, C. and Wang, J. (2015), “Hydrostatic seasonal state model for monitoring data analysis of concrete dams”, *Struct. Infr. Eng.*, **11**(12), 1616-1631.

Mata, J. and Tavares de Castro, A. (2014), "Constructing statistical models for arch dam deformation”, *Struct. Control Health Monit.*, **21**(3), 423-437.

Mirzabozorg, H., Hariri-Ardebili, M.A., Heshmati, M. and 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 Struct. Eng.*, **1**, 6-12.

Palumbo, P. and Piroddi, L. (2001), “Seismic behaviour of buttress dams: nonlinear modeling of a damaged buttress based on ARX/NARX models”, *J. Sound Vib.*, **239**(3), 405-422.

Rahimi, A. and Noorzaei, J. (2011), “Thermal and structural analysis of RCC dams by finite element code”, *Aus. J. Basic Appl. Sci.*, **5**(12), 2761-2767.

Sheibany, F. and Ghaemian, M. (2006), “Effects of environmental action on thermal stress analysis of Karaj concrete arch dam”, *J. Eng. Mech. - ASCE*, **132**(5), 532-544.

US Army Corps of Engineers (2003), “Time-history dynamic analysis of concrete hydraulic structures”, EM 1110-2-6051.