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Existing concrete dams: loads identification and finite element models validation

Martina Colombo*[1], Marco Domaneschi[2a], Aldo Ghisi[3b]

[1]PhD Student in Structural, Seismic and Geotechnical Engineering, Department of Civil and Environmental Engineering, Politecnico di Milano, Italy
[2]Contract Professor in Mechanic Science, Department of Civil and Environmental Engineering, Politecnico di Milano, Italy
[3]Professor in Mechanic Science, Department of Civil and Environmental Engineering, Politecnico di Milano, Italy

Abstract. A methodology for validating finite element models of existing concrete dams is presented in this paper. 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. The stiffness effect of the rock foundation and the surface degradation of concrete due to aging result crucial aspects to be accounted for an accurate validation of the models and 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 significant case studies: a buttress gravity and arch-gravity dams.

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

1. Introduction

As in other European countries, 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 6/7 decades. A recently introduced Italian standard is also focused to account 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, for which would be necessary to define the reasons.

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*Corresponding author, PhD student, E-mail: martina.colombo@polimi.it.
[a] PhD, E-mail: marco.domaneschi@polimi.it.
[b] PhD, E-mail: aldo.ghisi@polimi.it.

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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).

Also the physical-mathematical model of a dam-foundation system is part of the SHM inspections. 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.

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 static monitoring is analyzed using statistical and/or deterministic models: statistical models relate the present and the past behavior of the dam; deterministic models establish the relationship between the loads and the dam response, defined by a structural analysis.

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).

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. The comparison between the structural response evaluated by FE analyses and the effective response of the dam is an essential procedure for the real behavior interpretation. For effectively matching results of numerical and experimental data, the procedure of the model updating 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, among the others boundary conditions and material propertie, as shown in Bayraktar *et al.* (2011).

The stiffness distribution into the rock mass and into the dam body represents a crucial 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 these 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 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 gravity and arch dams, this article shows a method to proceed to the FE models preparation and validation accounting for available monitoring data. 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 standard (static, thermal and seismic analyses).

Numerical analyses are performed in typical 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.

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In this work the effectiveness of the models is evaluated by comparing results in terms of displacement with corresponding monitoring data. Therefore, the loads, e.g. hydrostatic pressure and temperature variation, present at the beginning of the monitoring activity, have to be set as the initial conditions for the FE simulations. Thus, 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.

2. Solid and finite element model of dam-foundation system

The first step of the analyses is to create a geometric solid model of the dam-foundation system. In the following, dams of two different types are considered: a gravity buttress and arch-gravity dams. 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 region, constituted by the two maximum height buttresses (see Fig. 1, in which The gravity dam is represented by the typical central slice), 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.

Fig. 2 depicts the solid models belonging to the arch-gravity dams, defined, as for the gravity buttress dam, through the original design tables.

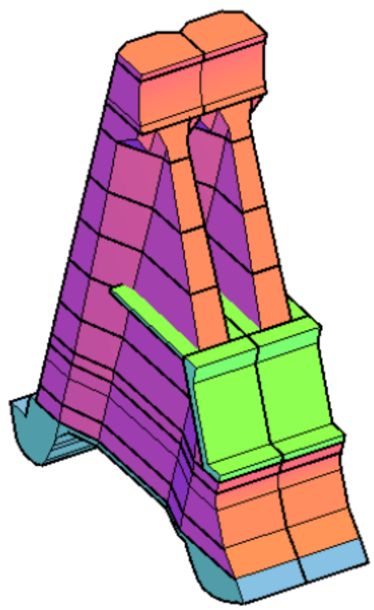

Fig. 1. Solid model of the central part of the gravity buttress dam.

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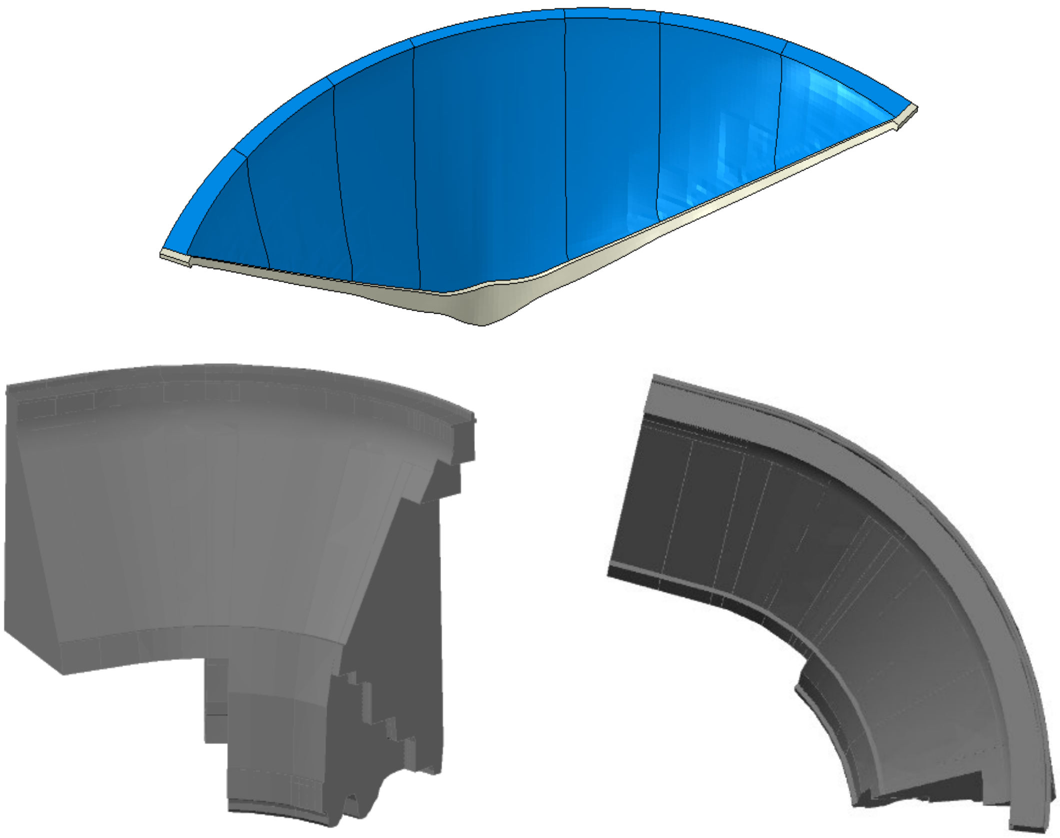

Fig. 2. Solid models of arch-gravity dams.

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. 3 and 4).

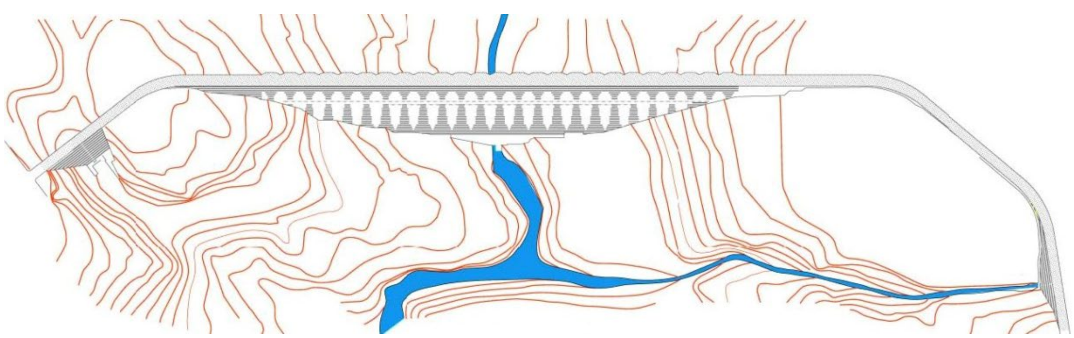

Fig. 3. Reservoir map at downstream part of the gravity buttress dam

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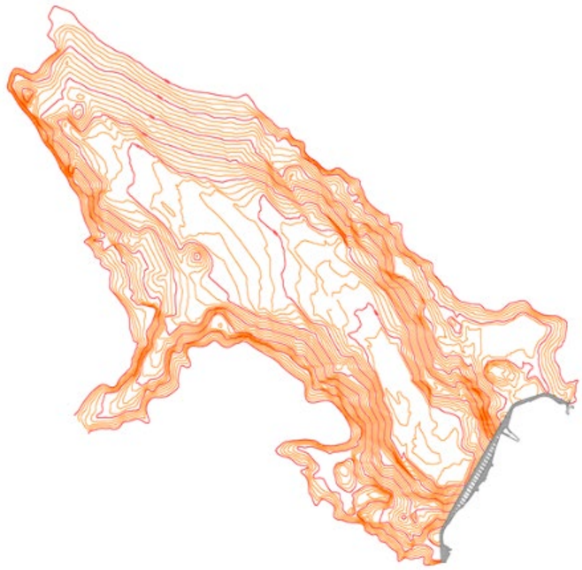

Fig. 4. Reservoir map for the gravity buttress dam.

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. Fig. 5 shows an example of a complete dam-foundation solid model for an arch-gravity dam. Finally, complete dam-foundation FE models of typical arch-gravity and buttress dams are depicted in Fig. 6(a)-(b).

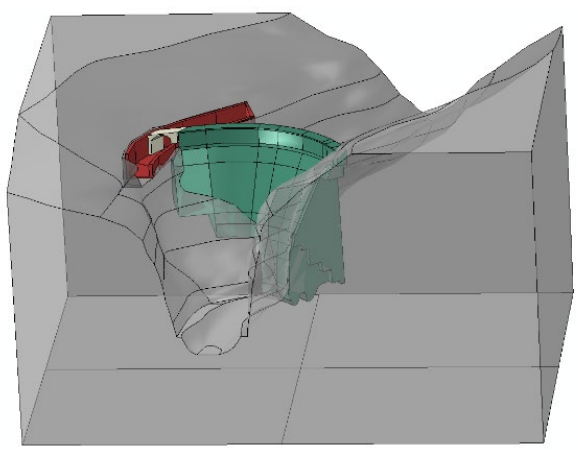

Fig. 5. Complete dam-foundation solid model for arch-gravity dam

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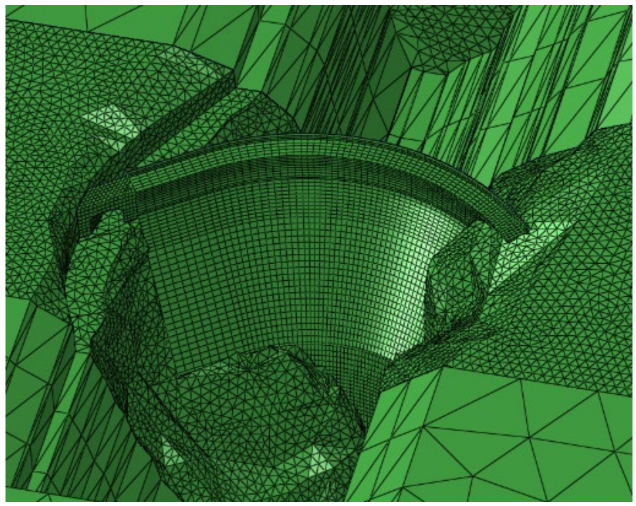
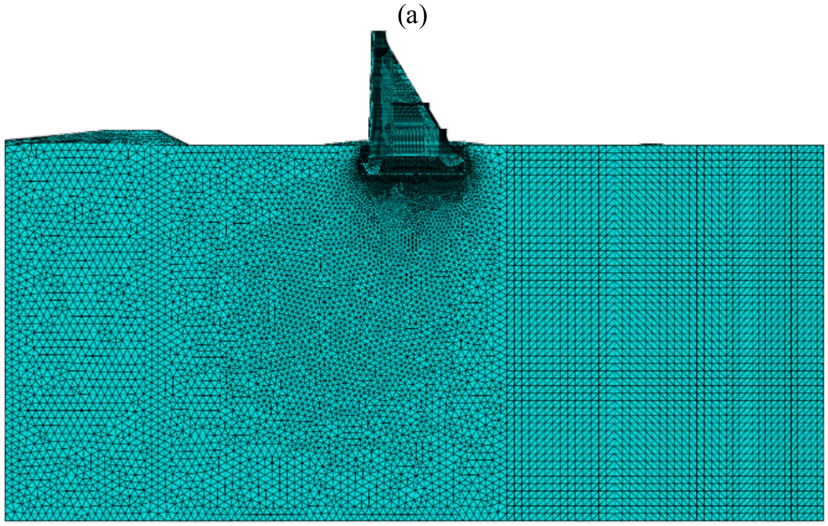


(a)



(b)

Fig. 6. FE models of (a) arch-gravity and (b) of central block of a buttress dams, including foundations

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, i.e. within the safety level defined by the designer and approved by the supervising agency.

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

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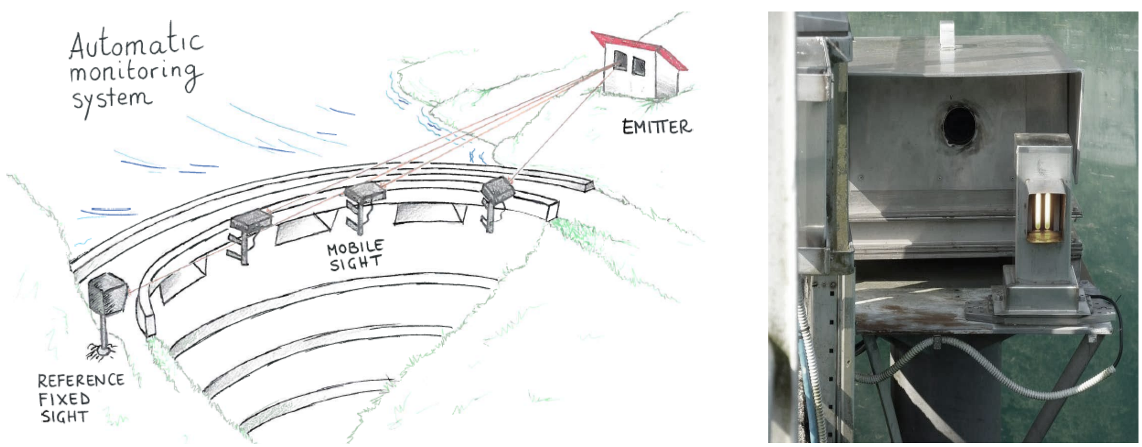
simultaneously perform analyses processes and comparisons with observations; minimum time between measures and information processing.

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: reservoir, temperature (in the air, water and concrete domain), precipitations (rain and snow), weather conditions (humidity, pressure and wind), ice thickness, reservoir bathymetry and seismic events. The response quantities are: 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 measured 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 on the dam type (arch, gravity or buttress), material, service life, dam dimensions, reservoir capacity and risk related to the downstream population density. Fig. 7(a)-(b) reports a typical monitoring scheme for an arch-gravity dam and a collimator.



(a) (b)

Fig. 7. Monitoring scheme for (a) an arch-gravity dam and (b) a collimator

4. Seasonal loading conditions

In this work the validation of the FE models is conducted exploiting quasi-static seasonal loadings, represented by hydrostatic and thermal actions. Thus, 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 absorbed by the dam prior to the installation of the monitoring system, therefore, herein disregarded.

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4.1. Temperature variations

Heat transmission into the dam body is typically conductive and can be modeled through a standard thermal FE analysis. A situation in which the boundary conditions are easy to be imposed is when 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. 8), as for the dams studied in this work. Otherwise, radiation and convention boundary conditions should be applied.

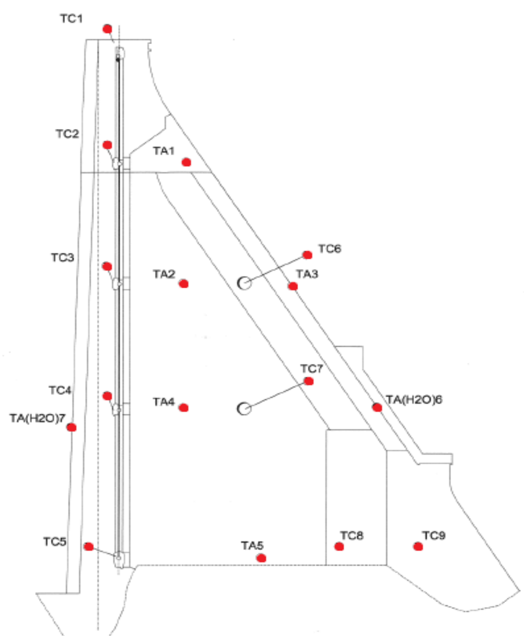

Fig. 8. Example of thermometer network placing in the central section of a buttress dam

Sinusoidal functions (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;
ω is the circular frequency;
φ is the sinusoidal phase.

Fig. 9 reports an example of temperature measurement by automatic thermometer and of the corresponding approximating function.

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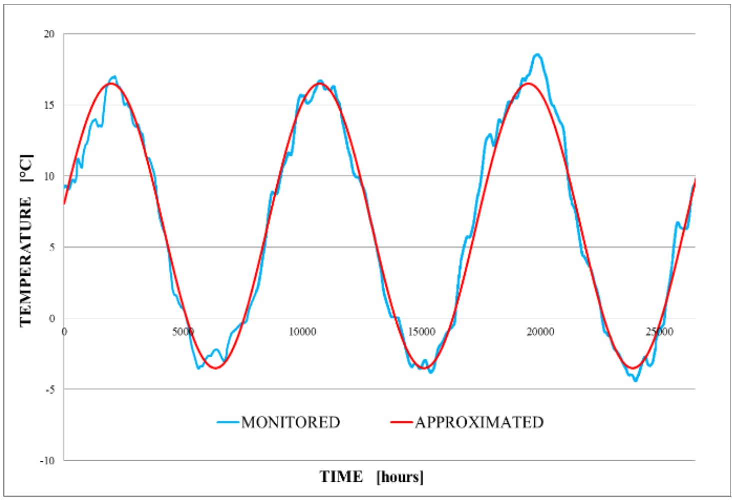

Fig. 9. Temperature recorded by an automatic thermometer and corresponding approximating function

4.2.Hydrostatic loading

The reservoir level variation can be also considered periodic. For one of the dam studied in this work, Fig. 10 gives the monitored water 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, while the maximum is in autumn.

Temperature time histories on the dam upstream surface depend on the evolution of the reservoir level.

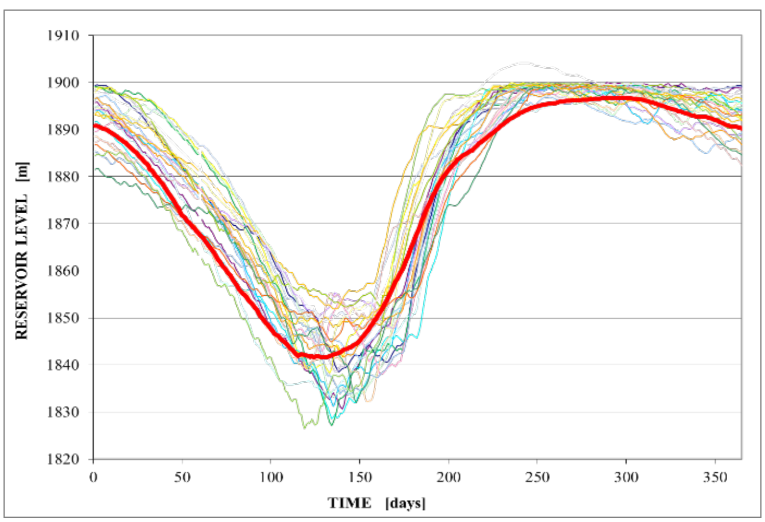

Fig. 10. Reservoir level and corresponding approximating function, with t=0 representing the 1st January

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4.3. Thermal analysis

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.

In this section a 3D transient thermal analysis, which defines the stabilized annual thermal cycle for a dam, and an elastic analysis, which gives the effects in terms of stresses due to the thermal deformations, are reported. The hydrostatic load and 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.

Legér and Leclerc (2007) evaluated the solution for the heat conduction in a wall, on the sides of which sinusoidal temperature are imposed. However, in order to consider the heat transmission by conduction through a more general approach, 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.

The study of the heat transmission by conduction is carried out through the Fourier equation (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];
ρ is the density [kg/m^3];
Q is the heat 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 (stabilized cycle). It is performed 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. 11), assumed also as reference temperature for the evaluation of the thermal strains. This represents the first step of the analysis, called “stationary step”. Then, a second step is developed, necessary for determining the temperature variation $\Delta T(x,t)$.

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. 12(a)-(b): 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 and are defined by Eq. (3):

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

where:
α is the thermal dilation coefficient.

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The evaluated thermal strains, used as input in the elastic mechanical analyses, define with the other loading conditions the stress state configuration.

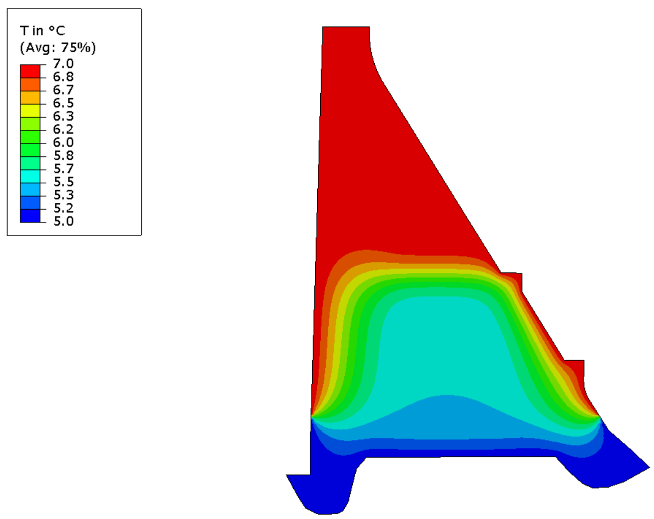
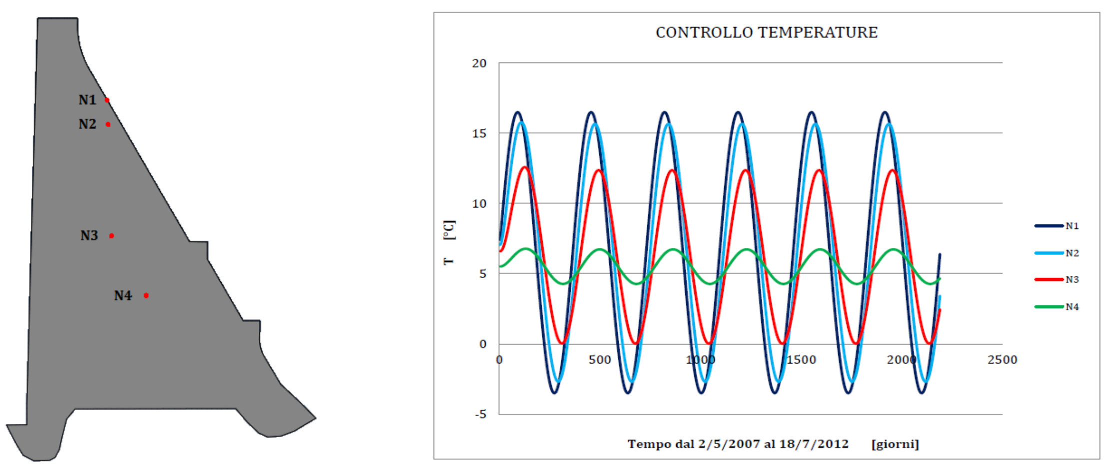


Fig. 11. Annual average value of temperature, used as input in the stationary step



(a) (b)

Fig. 12. Node disposition (a) and temperature behavior (b) in the gravity buttress dam

5. Stiffness distribution: rock foundation and micro-cracked concrete

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

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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. 13, in which the thickness of degradation area is about 2 meters). According to the analyses carried out, such damage could be caused by seasonal thermal self-equilibrated stresses.

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. 14).

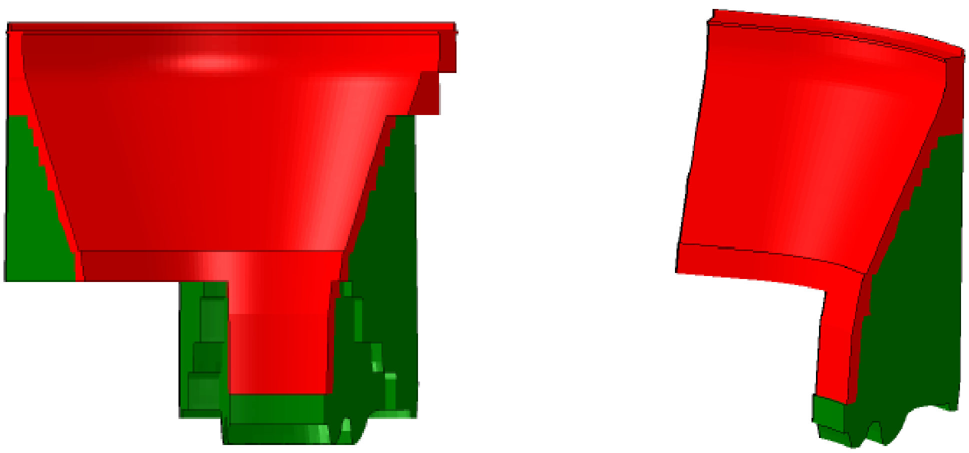

Fig. 13. Elastic modulus distribution in the arch-gravity dam (original value in green; reduced value in red)

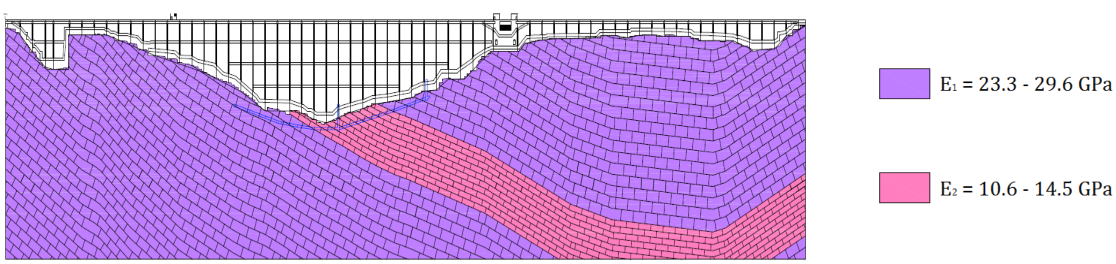

Fig. 14. Rock foundation characterization for the buttress dam

6. 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;

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- displacements, by making a comparison between the displacement response of the FE model under the effects of seasonal loads (previously defined in detail) with corresponding monitoring displacement measurements.

Figs. 15 and 16 show an excellent correspondence, respectively in terms of temperature and crest displacement (upstream-downstream direction) of the crown of the dam, between the monitoring and the FE outcomes.

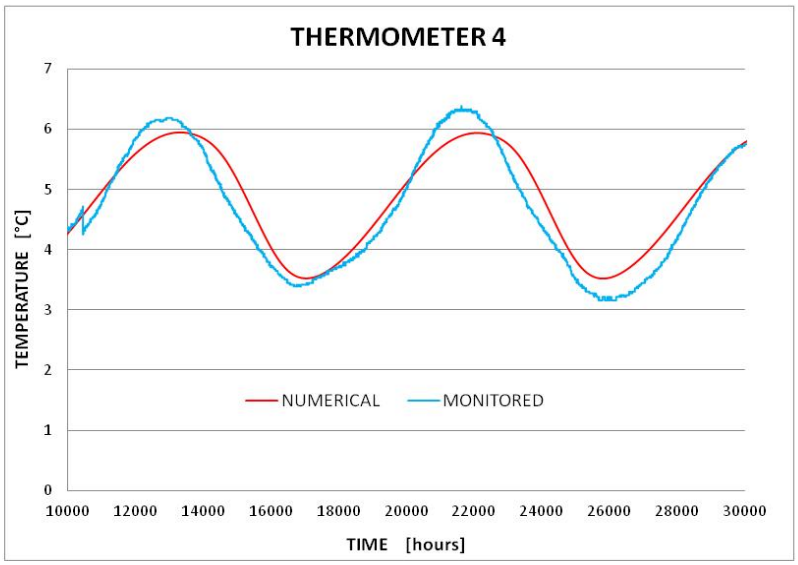

Fig. 15. Comparison between monitoring data (temperature by thermometers) and numerical results for the gravity buttress dam

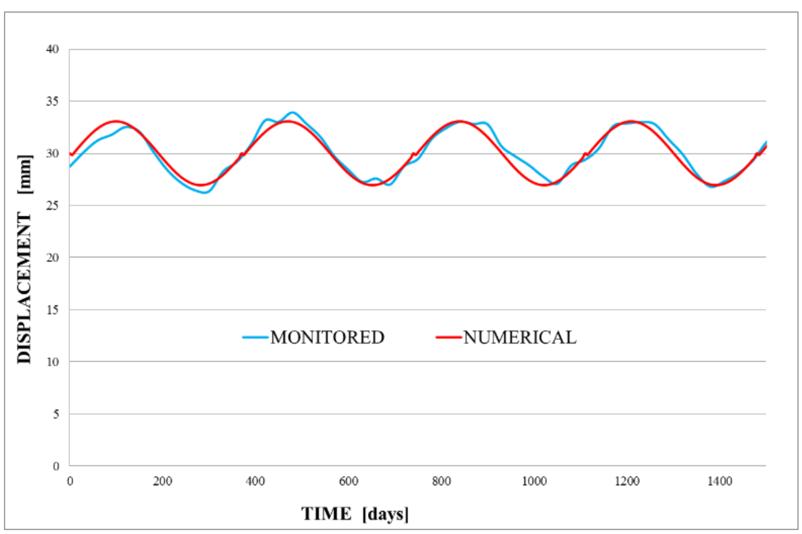

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Fig. 16. Comparison between monitoring data (upstream-downstream displacements) and numerical results for the arch-gravity dam

7. Conclusions

The structural assessment of existing concrete dams is nowadays regulated by new standards requirements, where the use of numerical models, such as the finite element ones, is usually 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. Existing large concrete dams of different typologies represent the case studies.

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 identification-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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