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Diagnostic analysis of concrete dams based on seasonal hydrostatic loading[☆]

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ABSTRACT

The procedure proposed and examined in this paper for diagnosis of possible damage in aged large concrete dams can be outlined as follows. Zone-wise uniform Young's moduli of concrete are traditionally the parameters to identify as representative of structural damage due to past physico-chemical processes or/and extreme loads. Change of reservoir level with annual periodicity in plant service is considered as inexpensive significant external action for nondestructive diagnostic experiments. Many displacements, concomitant with the transition from highest to lowest level, are measured on the downstream surface of the dam by radar instruments, which at present are promising innovations in dam engineering. Clearly nonnegligible contributions to measurable displacements due to seasonal thermal effects are taken into account by temperature measurements at time intervals through thermometers inside the dam, identification by them of parameters governing simplified thermal boundary conditions, time-dependence expressed by truncated Fourier series over a one-year period. Finally, damage diagnosis is carried out by minimization, with respect to the sought Young's moduli, of a batch discrepancy function between measured and computed displacements, as inverse analysis in a linear thermoelasticity context. The proposed method is computationally validated also through its stochastic extension.

1. Introduction

A significant percentage of existing concrete dams, particularly in Europe and North America, after a service life of several decades exhibits some kind of structural deterioration. The most frequent deteriorating occurrence is the physico-chemical process called Alkali–Silica Reaction (ASR). After a latency of about a decade and before saturation, over an active period of 30–40 years, such process generates a degradation of stiffness and strength and an expansion in the affected concrete; this expansion in turn gives rise to self-stresses and sometimes and somewhere to cracks. Only after the 1980s has an understanding of ASR gradually been achieved, while practical predictive modelling of it still represents a research challenge in multiphysics computational mechanics and dam engineering, see e.g. [1,2].

Other causes of possible structural damage, alternative to ASR or concomitant with it, are extreme external actions, such as earthquakes, hydrostatic loading during exceptional floods, or slow orogenetic motions in the surrounding geological system involving the dam foundation. Possible consequences, difficult to detect and quantitatively assess by local tests, may consist of diffused cracking with reduction of local average stiffness and strength in concrete masses, see e.g. [3]

In view of the above mentioned circumstances and of their obviously important implications (not only technical but also social and economical), more and more research efforts are devoted to diagnostic analyses of large concrete dams, namely to methodologies apt to identify locations and entities of possible structural damage.

The approaches and procedures so far developed for dam diagnosis can be classified as follows: (a) reliability assessment by evaluations of long-time monitoring results and comparisons with past behavior of the same dam and/or other monitored similar dams, see e.g. [6]; (b) local identification of concrete constitutive parameters and of stresses on the surfaces by flat-jacks, see e.g. [5], and in-depth by overcoring or dilatometric techniques, see e.g. [4]; (c) dynamic excitation by vibrodynes (or, occasionally, by some mild seismic shock), measurements through accelerometers and identification of Young's modulus distribution based on modal analysis in linear dynamics (e.g. [7]); (d) hydrostatic loading due to "fast" (a few days duration), usually ad hoc, changes of water level in the reservoir, displacement measurements by instruments such as pendula and collimators and inverse analysis of elastic moduli through a finite element model (linear-elastic or nonlinear if joint sliding is envisaged and accounted for), see e.g. [8,9]; (e) same technique as in the preceding case, but exploiting seasonal water variations, which are often implied by the plant operations and, hence, are rather inexpensive.

[☆] This paper is dedicated to the memory of Professor John Martin, recently commemorated in a IUTAM Symposium at Cape Town.

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A meaningful difference between case (d) and (e) arises from the need in (e) of taking into account thermal effects and their contributions to the measurable displacements. In (e) measured displacements may include an addendum due to viscous (creep) behavior of stressed concrete, an addendum which is generally negligeable (and is herein neglected) with respect to hydrostatic and thermal loads in six months.

The statical diagnostic analyses (d) and (e) are deemed to become more and more frequent and successful in view of new experimental equipment provided by radar and laser technologies as temporary supplements to the above mentioned conventional permanent monitoring instruments. The significant advantages are: potentially higher accuracy of measurements; very substantial growth of the number of experimental data, made available by radar or laser "ad hoc" instruments. Such data practically consist of an accurate map of the displacement field over large portions of the downstream surface of the dam tested, see e.g. [10]. However, all techniques for overall diagnosis are expected to exhibit the following obvious limitations: (i) only elastic moduli can be estimated since the test must be confined to the elasticity range of the structural response in order to be "non-destructive"; (ii) there are regions of the dam volume, internal or near the foundation (such as the "pulvino"), where possible stiffness degradation has little influence on measurable displacements (as sensitivity analysis can evidence); (iii) seepage and pressurized water penetration into cracks and joints are local damages with structural consequences, which are difficult to quantify through overall inverse analyses and require diverse provisions, primarily visual inspection. These circumstances make often necessary local in situ tests, like those mentioned in (b).

In this paper the diagnostic technique (e) based on seasonal hydrostatic loading is investigated, by assuming that the radar equipment is available and that it measures displacements developed by the dam in about six months. The external actions considered are fluctuations of water level from maximum to minimum and temperature variations from summer to winter, both regarded as periodic in time. In Section 2 an arch-gravity concrete dam, already considered in an ICOLD benchmark workshop, [11], is assumed as a reference, described in terms of geometry and material properties and modelled by the finite element method. Section 3 is devoted to a preliminary thermal analysis, which exploits the reasonable assumption of annual periodicity and, hence, is carried out with computational efficiency by truncated Fourier series expansions. In Section 4 the overall thermoelastic model is introduced. Section 5 contains the description and application of a procedure for the calibration, based on thermometric measurements inside the dam, of formulae established by various authors for the assessment of simplified thermal boundary conditions on concrete dams. The problem of damage diagnosis is addressed in Section 6. The inverse analysis procedure is validated numerically, i.e. it is based on simulations which provide "pseudo-experimental" data. The parameters sought as quantitatively representative of damage are Young's moduli distributed over a number of dam zones, uniformly over each of them. The identification is performed by means of a batch, first-order optimization (the "Trust Region" algorithm). In view of possible absence of objective function convexity, its values at solution is checked and diverse initialization are employed in order to avoid local minima. The measurement random uncertainties are considered and their consequences on the estimates are stochastically quantified by a Monte Carlo approach. Section 7 is devoted to closing remarks on achieved results and future prospects of research on open problems.

Notation. Bold symbols are used for matrices and vectors. Superscript T means transpose. A superposed dot indicates derivative with respect to time t.

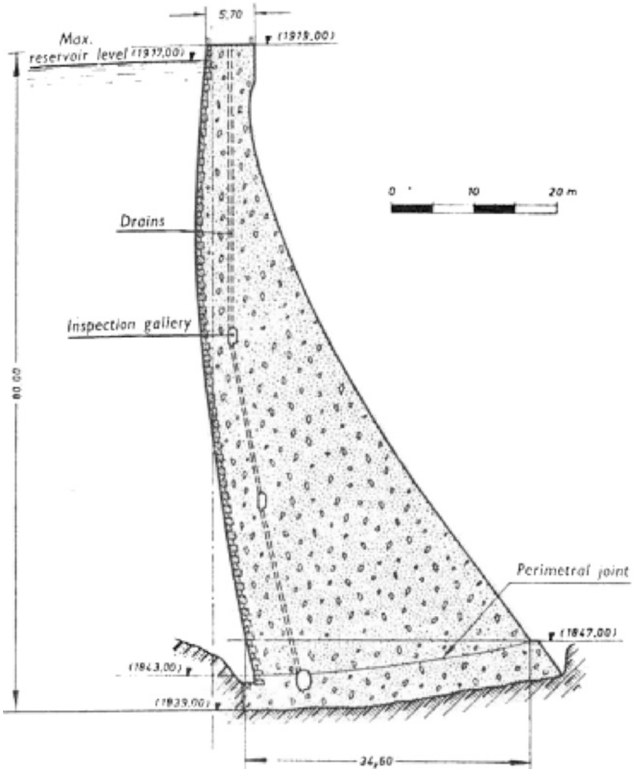

Fig. 1. Central cross-section of the reference arch-gravity dam.

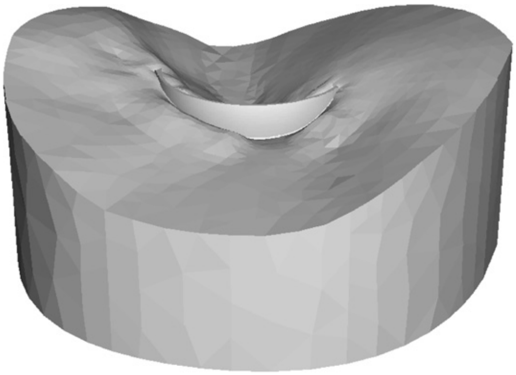

Fig. 2. Finite element modelled domain of the dam–foundation system.

2. A reference case history and its model

The diagnostic analysis procedure proposed in this paper will be developed with reference to a real-life situation specified below as for the main technical features relevant to the present purposes. The dam (see Fig. 1) belongs to the Piantelessio hydroelectrical power plant in Italy, described in [11] for the 2001 ICOLD benchmark. The quite significant upstream drift of the horizontal crown displacements evidences the presence of ASR, still in progress at present (2007). The structure considered herein is a concrete arch-gravity dam characterized by the following data: maximum height 80 m; crown length 515 m at 1919 m a.s.l.; maximum reservoir level 1917 m a.s.l.; minimum level 1848 m a.s.l.; concrete volume 380 000 m^3. The geometry of the dam and its foundation (including parts of the surrounding rocks) is depicted in Fig. 2, which also visualizes the domain considered for the formulation of analysis problems, to be solved by the finite element (FE) method by assuming zero displacements on the boundary with adjacent geological formation. The adopted FE space discretization involves 27 366 tetrahedral linear elements