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Statistical modelling of thermal displacements for concrete dams: Influence of water temperature profile and dam thickness profile

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ABSTRACT

Several factors are acting on concrete dams and affect dam displacements: hydrostatic load, thermal effect and irreversible phenomena (creep, swelling …). The different influences need to be quantified for the analysis of monitoring measurements. In most statistical models for the dam behavior analysis, the thermal effect which is often the main contributor to the total displacement is introduced only by means of the dam temperatures. Recently Tatin et al. (2015) have introduced a global gradient across the dam of the temperature bringing an additional bending effect. However, the thermal gradient may be very different, even with opposite sign, from the top to the bottom depending on seasons.

In this paper, a statistical model accounting for the water temperature profile is proposed. In this original statistical model, the dam is discretized along its height in n layers on which both mean and gradient of the dam temperature are computed for the evaluation of the thermal effect. It implies $2{\cdot}n$ new explicative variables for the statistical model yielding a reduced dispersion of the residuals. However, statistical compensation occurs from one layer to the next leading to unrealistic influence functions along the height of the dam. In order to reduce this effect, the statistical problem is constrained by imposing a polynomial approximation of influence functions. The parameters of the polynomial may be estimated either beforehand by means of the dam numerical model or directly by the statistical process. The number of additional degrees of freedom of the statistical process is thus reduced but can still describe the effects of both profiles of the water temperature and the dam thickness on dam displacements. For the model construction and validation, an arch dam is modelled by means of the finite element method and serves as a virtual case study. Although results show only a slight reduced residual dispersion, physical meaning of the model to the intermediate quantities is increased.

1. Introduction

In order to detect any possible anomalies, and to warn of any change which could endanger their safety, it is essential to monitor dams. Therefore, displacements, pressures and flow rates are classically measured. This contribution focuses on dam displacements analysis. Dam displacements are generally measured by direct or inverted pendulum, although other instruments (e.g. collimators, laser, radar, etc.) could be employed. Measured displacements are influenced by various factors such as hydrostatic load, thermal conditions and irreversible phenomena (creep, alkali-aggregate reaction, adaptation, consolidation, damage, cracking …). The part of the displacement induced by external periodic influences (thermal and filling conditions) is large compared to irreversible ones (in one year, the irreversible part is usually less than 1% of the reversible part). Thus, the simplest analysis which consists in plotting measured displacements as a function of time is generally not able to separate the different contributions and to detect the irreversible part.

Statistical modelling is employed in various domains [1] and consists, for dams, in a mathematical formulation of the existing relationships between environmental factors (water level, temperatures) and their behavior (displacements, pressures, flow rates). Even if, nowadays, different statistical processes are developed to interpret dam displacements (independent component analysis [2,3], blind source separation [4], principal component analysis [5,6] or artificial neural networks [7–10], etc.), multilinear regression remains the main method used in dam engineering.

The most common multilinear regression model, called HST

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(Hydrostatic, Season, Time), has been developed by EDF (Électricité De France) in the 1960s [11–13]. During several decades, results have confirmed the reliability and the soundness of this method [14–16] commonly employed in several countries [17–19,6]. However, although for concrete dams thermal loads are often the main contributors to the total displacements, this model assumes that thermal displacements follow a perfectly seasonal evolution (one-year period harmonic function) leading to insufficient performances, especially during periods significantly colder or warmer than seasonal average. Thus, it is essential to estimate this influence accurately, when interpreting new measurements [20–23].

Several approaches have been proposed to improve the modelling of the thermal influence by accounting for real temperature evolution and expressing the temperature field in terms of linear effective temperature. For instance, some statistical models explicitly consider data from thermometer embedded in the concrete mass [24–27] or consider delayed air temperature (HSTT model for instance [28]) instead of internal thermometer which are not available for the majority of dams. These statistical models enable to reduce significantly the residual dispersion of the HST model and reduce the anomalies induced by exceptional thermal conditions. As they are based on a deterministic structural calculation (the thermal variables), these models are called "hybrid" models in opposition to "purely statistical" (e.g. HST model) or "purely deterministic" models (e.g. finite element (FE) model).

A preliminary analysis based on the finite element models of two dams, a gravity dam and an arch dam, has shown the relative contribution of several thermal effects [29,23]. Both the solar radiation and the water temperature contribute for a large amount to the residual dispersion. Since part of the solar radiation is accounted for in the seasonal function, the so-called HST-Grad model [30], based on 1D thermal diffusion, has been developped to take into account the mean and the gradient of the dam temperature.

However, on one hand the vertical gradient of the water temperature is not accounted for, and on the other hand, the dam is modelled as a 1D medium with an equivalent thickness, which does not take into account the dam shape. In some case, the water temperature must be introduced accurately, since its evolution, both in space and time, might be highly perturbed (e.g. thermal convection in the reservoir, power production, snow melt, presence of ice at the reservoir surface, etc.).

After the description of the used numerical framework in the first part, the new statistical model proposed called HST-Layer, will be presented. Finally, this new hybrid model will be validated in terms of displacements on the same dam but both on the virtual finite elements case and on real monitoring data.

2. Dam behavior analysis based on a FE model

2.1. Numerical mock-up

A finite element model is used as a numerical mock-up for virtual testing of a real structure. Therefore, a 3D finite element model of a French arch dam (Fig. 1a) has been developed and is considered as a reference case to build and validate different approaches. This dam has been chosen for the present study because temperatures are measured in the dam body with seven embedded thermometers which are helpful to validate the numerical model. The geometrical characteristics of the dam are:

- Height/radius: 73 m/120 m
- Thickness at the top/at the bottom: 4.5 m/16 m
- Crest length/level: 220 m/943 m

The space discretization (mesh) of the dam has been built with an element size of about 1 m to accurately capture the displacements due to daily temperature (Fig. 1). The transient simulation is performed with a time step of one day which is a good compromise between computational effort and accuracy of the results.

2.2. Boundary conditions

In this model, the thermal field is calculated from air and water temperatures, solar radiation and also convective and radiative exchanges with the surrounding environment. Time-dependent boundary conditions are applied in terms of reservoir level, air and water temperatures, all measured on site. The boundary conditions applied to the foundation are zero normal displacement and zero normal thermal flux. All the thermal and mechanical boundary conditions considered in the model are summarized in Fig. 2. The water temperature is imposed by a Dirichlet boundary condition whereas the air temperature and the solar radiation are taken into account with a Neumann boundary condition.

Air temperature, water temperature and solar radiation come from in situ measurements. Indeed, in order to validate our original approach, the instrumentation set of the dam has been completed with eight temperature sensors vertically distributed over the upstream face of the dam to get the water temperature profile. Measurements are on a daily basis and one year of measurement is available. The water temperature T_w profile (Fig. 3) is approximated by an exponential law (Eq. (1)) which depends on time t, the water level y_w, the height H of the dam, the reservoir bed temperature T_{bot} and the surface temperature T_{surf} [31]. The parameter Φ is calibrated with real measured profiles.

$$T_w(y_w,t) = T_{bot}(t)\cdot\frac{1-e^{-\Phi\cdot y_w}}{1-e^{-\Phi\cdot H}} + T_{top}(t)\cdot\frac{e^{-\Phi\cdot y_w}-e^{-\Phi\cdot H}}{1-e^{-\Phi\cdot H}} \tag{1}$$

It is known that the maximum water density is reached for a temperature of 4 °C [32] which means that water temperature profiles cannot cross the vertical lines at 4 °C (except in particular conditions i.e. when the reservoir is cover by ice, near water intake structure where significant water mixing occurs,…). The consequence of this physical properties is clearly observed on the measured water temperature profile. Indeed, in a shorter time base (not shown here), one has observed a complete temperature homogenisation within few days when

(a)

(b)

Fig. 1. (a) Photography of the dam and (b) finite element mesh.