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Thermal displacements of concrete dams: Accounting for water temperature in statistical models

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ABSTRACT

Measurements of concrete dam displacements are influenced by various factors such as hydrostatic load, thermal effect and irreversible phenomena (creep, swelling, etc.). To interpret measurements and improve the assessment of irreversible effects, splitting the different influences is necessary. For this purpose, models based on statistics and physics are commonly employed in engineering studies. Although they are efficient in most cases to analyse the displacement of concrete dams, these models are built on a certain number of hypotheses, necessary to write "simple" mathematical relationships, but leading to uncertainties. To evaluate the suitability of these physico-statistical models (importance of the hypotheses) and to improve it, a 2D finite element (FE) model has been developed as a heuristic case. This study shows the importance of water temperature and temperature gradient in the assessment of the thermal displacements. So, a new physico-statistical model is proposed to account for these phenomena. The evaluation of its performance on both the FE heuristic case and real cases shows that the improved assessment of thermal effects on reversible phenomena leads to a reduced uncertainty on residuals. Thus, the proposed approach yields to a better assessment of irreversible trends.

1. Introduction

Safety is an important issue for dam management. As the structural vulnerability increases with the dam ageing, it is essential to monitor dams for ensuring their safety over the long term. Dam surveillance mainly consists of analysing gathered data in order to verify that the dam is functioning as intended, to detect any possible anomalies, and to warn of any change which could endanger its safety. Displacements, pressure and flow rates are classical measures for dam safety.

This contribution focuses on dam displacement analysis. Although a lot of instruments (e.g. collimators, laser, radar, etc.) can be employed, dam displacements are generally measured by direct or invert pendulums. They are influenced by several factors such as hydrostatic load, thermal conditions and irreversible phenomena (creep, alkali-aggregate reaction, adaptation, consolidation, damage, cracking, etc.). The simplest analysis consists in plotting measured displacements as a function of time, or as a function of the reservoir level, but this type of graph is difficult to analyse because of dispersion due to external reversible influences (thermal and filling conditions). Usually, in one year, the irreversible part of the displacement is less than 1% of the reversible displacement (e.g. for a 130 m height arch dam, the thermal displacements amplitude is about 20 mm, whereas its irreversible trend is about 0.1 mm per year). As a consequence, statistical models are commonly used to separate the influences of the different explicative factors, and then to observe anomalies or irreversible trends.

Statistical modelling is a classical approach in data analysis and is employed in various domains [1]. A statistical model is a mathematical formulation of the existing relationships between environmental factors (water level, temperatures) and dam behaviour (displacements, pressure, flow). By calibrating these models on the past behaviour of the dam, a diagnostic can be established on the recent behaviour which is expected to remain the same.

The most common statistical method in dam engineering is called HST (Hydrostatic, Season, Time) and has been developed by EDF (Électricité De France) in the 1960s [2–4]. With this model,

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the reversible influences can be assessed (hydrostatic and seasonal components) and subtracted to the measurements so as to highlight the irreversible behaviour of the dam. For several decades, the obtained results have confirmed the relevance and soundness of this method for interpretation of dam monitoring measurements [5–7]. This method is currently used in several countries [8–12].

However, in the HST model, thermal displacements are assumed to follow a perfectly seasonal evolution (one-year period harmonic function). As a consequence, the performance of HST is not always sufficient, particularly when time periods are significantly colder or warmer than seasonal average. For a majority of concrete dams, thermal displacements induce a large proportion of the recorded displacement. Thus, it is really important to identify this component accurately while interpreting newly recorded data [13,14].

Several approaches have been proposed to improve the modelling of the thermal influence by accounting for real temperature evolution. Statistical models that considered explicitly data from thermometer embedded in the concrete mass have been proposed [15,13]. Using directly concrete temperature measurements as explicative factors allows avoiding uncertainties due to heat transfer processes, especially at the boundaries. However, the thermometers give local informations which are not totally representative of the global temperature field. Thus, more sophisticated models have been developed to express the temperature field in term of linear effective temperature across the dam cantilever sections [13,16]. The approximation of the non-linear one-dimensional thermal field along the thickness of the dam by a linear equivalent one is considered as sufficient to estimate the global displacements [17,14,13,16]. Then, the temperature field along a cross section can be represented by its mean and its gradient. In these methods, an inverse heat transfer problem is employed to obtain the temperatures at the boundaries from temperatures recorded by the embedded thermometer and a direct heat transfer problem to rebuilt the linear effective temperature from the boundary temperatures. These statistical models, based on a deterministic structural calculation (the thermal variables), are called “hybrid” models in opposition to “purely statistical” (e.g. HST model) or “purely deterministic” models (e.g. finite element (FE) model).

Besides, after the exceptional 2003 European heatwave, a model based on the exploitation of the air temperature instead of internal thermometer (which are not available for the majority of dams) has been developed [18]. The model, called HSTT (Thermal HST) is an hybrid model, it keeps the seasonal function of HST but adds a corrective term which accounts for delayed deviation of the daily air temperature to its seasonal average. This method enables to reduce significantly the residual dispersion of the HST model and reduces the anomalies induced by exceptional thermal conditions.

Nevertheless, since water temperature, solar radiation and coupling phenomena such as thermal boundary conditions depending on the reservoir level are not directly taken into account (the influence of these phenomena on the displacement can be partially captured by the seasonal function), the thermal state of the structure cannot be correctly assessed. Moreover, in the HSTT approach, the thermal state of the structure is reduced to the estimation of the mean temperature. However, according to [14,13,16], the mean temperature but also the temperature gradient across the dam are important for calculating the global displacements. For all these reasons, the residual dispersion of the model may remain high in some cases (some few tenths of millimetres) and the irreversible behaviour difficult to appreciate.

The objective of this study is to improve the assessment of the thermal displacements in the statistical analysis and thus to reduce the residual dispersion. A previous study has identified water temperature as an important source of dispersion for the HSTT model [19]. Based on this analysis, a new physico-statistical model has been developed by taking into account water temperature (and the temperature gradient generated by the difference between air and water temperature). This new hybrid model will be presented after a brief presentation of the HSTT model. Besides, a 2D finite element model of a gravity dam has been developed and will be considered as a heuristic case. Based on thermo-mechanical simulations, this model allows us to separate numerically the different thermal influences and will be employed to validate the capability of the new model to capture the thermal effect induced by water temperature and to compare its performance to HSTT. Finally, the new model will be validated on real monitoring data for several dams.

2. The HSTT model

HSTT is a hybrid physico-statistical model [18]. Its objective is to decompose the measurements in a sum of reversible and irreversible influences to appreciate the behaviour of the dam. Each influence is modelled by a mathematical expression. The global model is a multi-linear regression formed by the sum of all the expressions and is adjusted on the measurements by the least square method. The HSTT model decomposes the displacements into three components:

- A time-dependent irreversible component which represents the long term behaviour of the dam (creep, adaptation, swelling, consolidation, settling, etc.). Although exponential functions can be used (to represent the evolution of concrete creep at early age), for the sake of simplicity, irreversible phenomena are modelled in this contribution by a linear function of the time t (it is assumed on the analysis period chosen in this study that the creep phenomenon is cushioned):

$$f_1(t) = a_1 \cdot t \tag{1}$$

- A hydrostatic reversible component which represents the displacements due to hydrostatic loading. It is modelled as a fourth degree polynomial function of the variable $z = \frac{RN-h}{RN-R_{empty}}$ (RN is the normal reservoir level, R_{empty} is the empty reservoir level and h is the actual reservoir level):

$$f_2(z) = a_2 \cdot z + a_3 \cdot z^2 + a_4 \cdot z^3 + a_5 \cdot z^4 \tag{2}$$

- A thermal reversible component which represents dam displacements due to temperature variations. This component is decomposed into two functions:
  - A seasonal function which represents the thermal displacements induced by the seasonal part of thermal loads. The dam response to seasonal phenomena is assumed to follow periodic evolution of period one year. Thus, this seasonal influence is modelled by the two first terms of the Fourier series decomposition of a one year periodic signal. Accounting for the second term of the Fourier series generally improves the statistical analysis as there is seasonal but non-harmonic thermal phenomena (e.g. water temperature, solar radiation). So, the seasonal function is the sum of harmonic functions of the season angle S (the angle S linearly increases by 2π rad in one year):

$$f_3(S) = a_6 \cdot cos(S) + a_7 \cdot sin(S) + a_8 \cdot cos(2 \cdot S) + a_9 \cdot sin(2 \cdot S) \tag{3}$$

    It is worth noting that this seasonal function is the same than the one used in the HST model. Nevertheless, another form of this function can be found in the literature (e.g.