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# Probabilistic numerical modeling of an RCC dam construction

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ABSTRACT: In this paper, a thermo-chemo-mechanical model is applied to the simulation of the construction of a roller-compacted concrete (RCC) dam. The model accounts for the hydration degree evolution and its influence on the mechanical properties. The simulations are performed using a 2D plane-strain finite element analysis. Some parameters are given a random character in order to account for uncertainties about the material. A sensitivity analysis using the Random Balanced Design FAST (RBD-FAST) technique is performed. The described model is applied to a simplified 2D column on which a cracking density probability is evaluated via the Latin Hypercube Sampling method.

## 1 INTRODUCTION

The use of probabilistic tools within dam safety assessment has been increasing during the last two decades. However, the evaluation of a dam's safety has been mostly done based on expert's experiences and, more recently, via semi-probabilistic methods (since the introduction of the Eurocodes). This work (and the related PhD thesis in current development) aims to be a contribution in this domain by applying some probabilistic tools to propagate uncertainties and assess a target probability of failure. A layer-by-layer construction of the RCC dam is simulated using a thermo-chemo-mechanical model to describe the RCC behaviour. That model is based on the one presented by (Cervera, Oliver, & Prato 1999) and enables the account for the mechanical properties dependence on the hydration reaction evolution that occurs in RCC at early ages. A global sensitivity analysis using the Random Balanced Design Fourier Amplitude Sensitivity Test (RBD-FAST) method, is performed over the thermal model in order to understand the influence of the input variability of each parameter on the model output. A random character is given to some RCC parameters and ambient conditions. Later, a concept of "cracking density" is introduced and the Latin Hypercube Sampling (LHS) method is used this time to propagate the previously identified uncertainties over the thermo-mechanical model of a 2D column. A cracking density probability is then evaluated over the 2D column model.

## 2 NUMERICAL MODEL

The roller-compacted concrete is a concrete which, as its nomination infer, can be placed and compacted by successive layers/lifts. It is widely applied in dam and road engineering. The RCC has a low cement content when compared to conventional concrete (CC). It will then produce less hydration heat, which is the reason why it allows greater construction rates, and consequent lower costs. Still, temperature gradients shall be controlled within the RCC structure in order to avoid cracking. RCC mechanical properties are, such as for CC, dependent on the chemical reaction evolution that occurs between cement (and additives) and water. Therefore, a thermo-chemo-mechanical model is needed in order to simulate the RCC behaviour. Several authors, such as (Cervera, Oliver, & Prato 1999, De Schutter 2004, Lackner & Mang 2004), developed different models to simulate this coupled behaviour of concrete. In this work, a model based one described in the work of (Cervera, Oliver, & Prato 1999) is adopted. In the following, the hydration model will be presented, followed by a brief description of the thermo-chemo-mechanical coupling.

### 2.1 *Hydration model*

The general heat transfer problem, assuming an isotropic medium, is described by equation 1, where $\rho$[kg/m$^3$] is the material density, $c$[J/(kg°C)] is the specific heat, $T$[°C] is the temperature ($\dot{T}$ being its first time derivate) and $\underline{k}$[W/(mK)] is the (isotropic) thermal conductivity.

$$\rho \cdot c \cdot \dot{T} = \underline{\nabla}\left(\underline{k}\nabla T\right) + \dot{Q} \quad ; \quad \underline{\nabla} = \left(\frac{\partial}{\partial x}, \frac{\partial}{\partial y}\right) \qquad (1)$$

The rate of heat generation is given by equation 2, where $l_\xi$[kJ/m$^3$] is the (constant) heat of hydration per unit volume and $\xi$[.] is the hydration degree which expresses the evolution of the hydration reaction and varies, theoretically, between 0 and 1. In practice, the final hydration degree $\xi_\infty$ is considered less than 1.

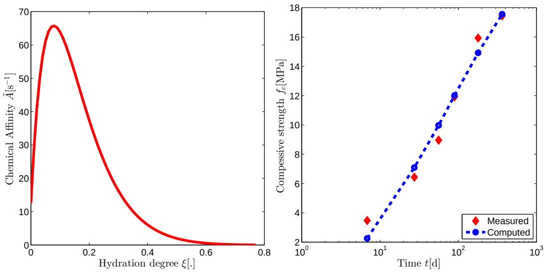
$$\dot{Q} = l_\xi \cdot \dot{\xi} \quad ; \quad \dot{\xi} = \tilde{A}(\xi) \cdot \exp\left(-\frac{E_a}{R \cdot T}\right) \qquad (2)$$

The hydration degree rate may be described by means of an Arrhenius-type formula, such as in equation 2, where $\tilde{A}(\xi)[s^{-1}]$ is the chemical affinity function, the activation energy is given by $E_a$[kJ/mol] and $R$[kJ/(K$\cdot$ mol)] is the universal gas constant. The $E_a/R$ ratio ranges between 3000 and 8000K (Cervera, Oliver, & Prato 1999). The chemical affinity function is described by equation 3 (Cervera, Oliver, & Prato 1999), where $k_\xi$, $\eta_{\xi_0}$, $A_{\xi_0}$ and $\overline{\eta}$ are material properties derived from the reactive porous media theory presented by Coussy (Coussy 1996).

$$\tilde{A}(\xi) = \frac{k_\xi}{\eta_{\xi_0}}\left(\frac{A_{\xi_0}}{k_\xi \cdot \xi_\infty} + \xi\right) \cdot (\xi_\infty - \xi) \cdot \exp\left(-\overline{\eta} \cdot \frac{\xi}{\xi_\infty}\right) \qquad (3)$$

The boundary conditions involve the heat flux at surfaces (equation 4), where $h$[W/(m$^2$$\cdot$K)] is the heat transfer coefficient, $T_{ext}$[°C] is the ambient temperature and $\underline{n}$ is a normal vector of the surface.

$$\frac{\partial T}{\partial \underline{n}} = \begin{cases} \frac{h}{k} \cdot (T_{ext} - T) \\ 0 \text{ if insulated surface} \end{cases} \qquad (4)$$



(a) (b)

Figure 1: a) Chemical affinity and b) Compressive strength evolution during isothermal test.

## 2.2 *Thermo-chemo-mechanical coupling*

The thermo-chemo-mechanical coupling used in this work is based on the one of (Cervera, Oliver, & Prato 1999), on which an aging degree is introduced. That aging degree ($\kappa$) is a function of both the temperature and the hydration degree (equation 5). The beginning of the curing phase is ruled by the parameter $\xi_{set}$, known as the mechanical percolation threshold.

$$\dot{\kappa} = \lambda_T(T) \cdot \lambda_{f_c}(\xi) \cdot \dot{\xi} \geq 0 \qquad (5)$$

$$\lambda_T(T) = \left(\frac{T_T - T}{T_T - T_{ref}}\right)^{n_T} \qquad (6)$$

$$\lambda_{f_c}(\xi) = A_f \cdot \xi + B_f \text{ , for } \xi \geq \xi_{set} \qquad (7)$$

Then, the mechanical properties, such as the compressive strength $f_c$, may be described as function of the aging degree (equation 8, where $f_{c,\infty}$ is the final compressive strength).

$$f_c(\kappa) = \kappa \cdot f_{c,\infty} \qquad (8)$$

## 3 PROBABILISTIC MODEL

The main objective of the probabilistic model used in this work is to assess the variability of the model output by accounting uncertainties inherent to some input parameters. In a first approach, a global sensitivity analysis is performed over the thermal model of the RCC dam construction, in order to assess the influence of input uncertainties on the output of the model. The Random Balance Design FAST (RBD-FAST) (Tarantola, Gatelli, & Mara 2006) is a sensitivity test derived from the Fourier Amplitude Sensitivity Test (FAST) (Saltelli, Tarantola, & Chan 1999). The FAST method is based on the variance decomposition, used here to compute the first-order sensitivity indices $S_i$. In this work, the RBD-FAST is chosen over the FAST method because of the increased number of needed simulations of the latter, for the number of random variables studied in this work (minimum of 570 against 250 simulations (Saltelli, Tarantola, & Chan 1999)). However, RBD-FAST leads to a lower accuracy for low values of the sensitivity indices. For further details about FAST and RBD-FAST the reader is referred to (Xu & Gertner 2008, Mara 2009).

Furthermore, the Latin Hypercube Sampling (LHS) method is applied to a 2D column thermo-mechanical model. The LHS is a Monte Carlo-based sampling technique on which each variable search space is divided into equal intervals of equal probability. The pairs of random variables are randomly chosen and combined. For further information about LHS the reader is referred to (Olsson, Sandberg, & Dahlblom 2003, Xu, He, Hu, Chang, Li, & Bu 2005).

The model parameters that are given a random character in this work are: the water-to-cement ratio ($w/c$) which will influence the final hydration degree $\xi_{\infty}$; the cement content ($c$[kg/m$^3$]) which will influence the hydration heat generated per cubic meter of material $l_{\xi}$[kJ/m$^3$]; the thermal conductivity ($k$[W/(mK)]); and the wind speed ($v_{wind}$[m/s]) which will influence the convection coefficient $h$[W/(m$^2$K)]. As a first approach, and because of the lack of statistical information, all four random variables $w/c$, $c$, $k$ and $v_{wind}$ are supposed to be independent and uniformly distributed. A set of 250 RBD-FAST computations were performed over the thermal model of the dam. A set of 150 LHS computations were performed over the thermo-mechanical model of the 2D column. The random variables used in this work are described in table 1. In the column model, a concept of fissuration index is introduced by equation 9, where $f_t$[MPa] is the tensile strength and $\sigma_1$[MPa] is the first principal stress. After being evaluated at each construction step, the “cracking density” ($\rho_f$, equation 9) may be found by dividing the number of points where $0 \leq I_f < 1.0$ for the total number of points discretized per constructed lift.

Table 1: Random variables for RBD-FAST and LHS

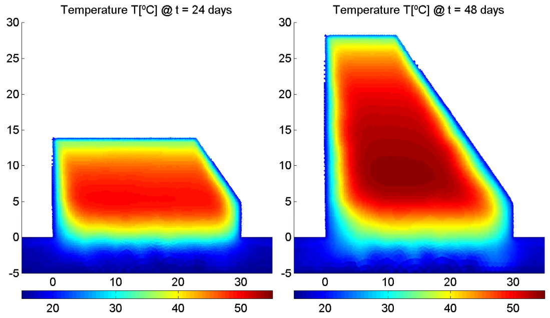
| $w/c$[.] | $c$[kg/m$^3$] | $k$[W/(m°C)] | $v_{wind}$[km/h] |
|---|---|---|---|
| $\mu = 0.6$<br>$CV = 0.1$ | $\mu = 220$<br>$CV = 0.15$ | $\mu = 2.96$<br>$CV = 0.25$ | $\mu = 17$ ($\mu_h = 27$)<br>$CV = 0.2$ |

$$I_f = \frac{f_t}{\sigma_1} \quad ; \quad \rho_f = \frac{N_{0 \leq I_f < 1.0}}{N_T} \tag{9}$$

## 4 APPLICATION

The dam model used in this work consists of an RCC gravity dam body of 28.2m high, 30m wide at its base level and with a downstream slope of 0.8. The foundation is also represented in this model in order to account for its thermal effect on the first layers of the RCC dam. Concerning the thermal boundary conditions, the bottom and lateral faces of the foundation are insulated, while all the dam faces interact with the surrounding environment by a heat flux exchange (previously described by equation 4). The dam construction simulation is performed by applying a construction scheme of 0.6m per day. The same initial and boundary conditions are applied to the 2D column model which is supposed to be representative of the behaviour of the center of the RCC dam. Exception made for the lateral boundary conditions, which are insulated in the 2D column model.

Regarding the environmental conditions, or “external thermal load”, it is characterized by a daily sinusoidal variation of the ambient temperature. This one will oscillate between $T_{max} = 30$°C and $T_{min} = 10$°C according to equation 10, where $\Delta T$[°C] $= (T_{max}$-$T_{min})$, $f$[d$^{-1}$] is the daily frequency and $\phi$[rad] is the phase. Wind effects can be taken into account via the convection coefficient $h$[W/(m$^2$K)]. Concerning the numerical model, the mesh is composed of 3300 triangular elements, the time-step is of 0.5[h] and the construction rate 0.6m/24h.



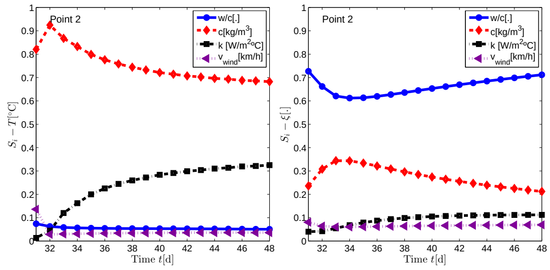
(a) (b)

Figure 2: Temperature surfaces during construction a) $t = 24$ days ; b) $t = 48$ days

$$T_{ext} = \frac{T_{max} + T_{min}}{2} + \frac{\Delta T}{2} \cdot \sin(2\pi f t + \phi) \tag{10}$$

## 5 RESULTS

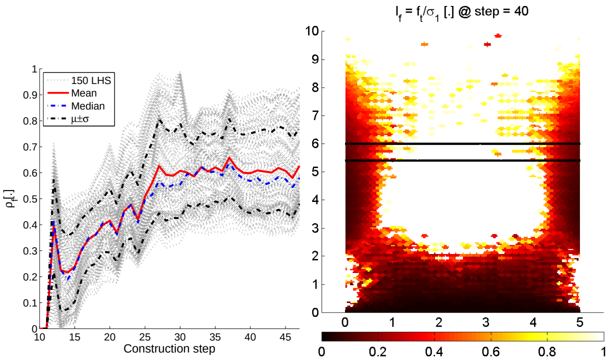
The statistical convergence of the results was verified and assumed to be sufficient for the application considered in this work. The global sensitivity analysis performed over the results of the RBD-FAST computation set leads to the obtention of the first-order sensitivity indices ($S_i$). The sensitivity indices traduce the contribution of each random parameter on the response of the model (in this case, on the temperature, hydration degree and aging degree evolutions). In Fig. 3 are plotted the $S_i$ obtained for RBD-FAST computation set concerning point 2 (point near the downstream face of the dam) for temperature $T$ (Fig. 3a) and hydration degree $\xi$ (Fig. 3b) as functions of time. It was observed that the $S_i$ values obtained for the aging degree $\kappa$ evolution are very similar to the ones obtained for the hydration degree $\xi$.



(a) (b)

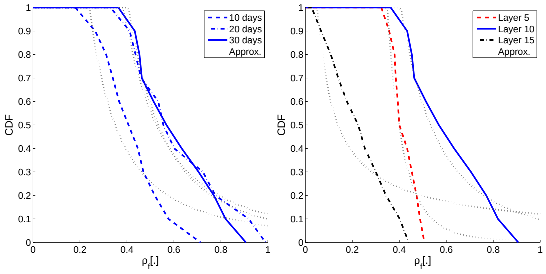
Figure 3: Sensitivity analysis results
a) $S_i$ over temperature at point 2 and b) $S_i$ over the hydration degree at point 2.

In figure 4a are plotted the obtained cracking densities $\rho_f$ at layer 10 (layer between 5.4 and 6m height), as well as their mean, standard deviation and median responses. In figure 4b is depicted the cracking index within the column at step 40 of the construction schedule. In black is enhanced layer number 10. Finally, the cumulative distribution functions (CDF) of $\rho_f$ are plotted in figure 5, first for layer number 10 at three different construction steps (figure 5a), and then for three different layers, one month after the construction of each one (figure 5b). The approximated CDFs are obtained via the following power function: $Prob[\gamma \geq \rho_f] = w \cdot \rho_f^{-\alpha}$.



(a) (b)

Figure 4: Cracking density on layer 10
a) 150 LHS ; b) Cracking index surface



(a) (b)

Figure 5: Cumulative Distribution Functions
a) Layer 10 at 10, 20 and 30 days after casting ; b) Layers 5, 10 and 15 at 30 days after casting

## 6 CONCLUSIONS

From the sensitivity analysis several conclusions may already be drawn: first of all, it may be concluded that the considered r.v. affect the results in different ways and magnitudes according to the emplacement of the analyzed point; the cement content will dominate the temperature responses both in the center and at the surface of the dam, even if for the latter its influence will decrease in time due to the increasing influence of the thermal conductivity; regarding $w/c$, it presents insignificant $S_i$ for temperature results; in what concerns $\xi$ results, it is $w/c$ that dominates the response; this means that the uncertainty induced in the chemical affinity curve via $\xi_\infty$ (which depends on $w/c$) does not significantly affect temperature within the dam body but it affects the hydration degree and therefore the mechanical properties, presenting a sensitivity index that varies between $0.6$ and $0.7$ during the dam construction; finally, the influence of $v_{wind}$ on both temperature and hydration degree is insignificant, exception made for the instant right after placing where $S_i \approx 0.12$ for temperature. After having concluded that $v_{wind}$ does not affects the model response, this parameter was given a deterministic character for the 150LHS performed over the 2D column model. The cracking densities were evaluated at different construction steps for the same layer, as well as for different layers at the same age. It was observed that different CDFs are obtained for different layers at different ages. The obtained CDFs should improve with the increasing of the calculations number. Also, the CDFs form resembles the one presented by the Japan Concrete Institute (Japan Concrete Institute 2012).

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