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Guy-De-Patience Ftatsi Mbetmi, Thomas de Larrard, Frederic Duprat

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Guy-de-patience Ftatsi Mbetmi

Université de Toulouse, LMDC UPS/INSA, INSA, 135 avenue de Rangueil, 31077 Toulouse cedex, France ; Université de Ngaoundéré, B.P. 454, Ngaoundéré, Cameroun (ftatsimb@insa-toulouse.fr)

Thomas de Larrard

*Université de Toulouse, LMDC UPS/INSA, INSA, 135 avenue de Rangueil, 31077 Toulouse cedex, France (*delarrard@insa-toulouse.fr*)*

Frédéric Duprat

Université de Toulouse, LMDC UPS/INSA, INSA, 135 avenue de Rangueil, 31077 Toulouse cedex, France (frederic.duprat@insa-toulouse.fr)

Abstract: Alkali-aggregate reaction (AAR) is a deleterious reaction that affects a large number of concrete structures, among which concrete dams, worldwide. It has been observed on dams built on each of the five continents. In France, they are about thirty affected dams, and in Cameroon AAR have been noticed on the Song Loulou hydropower dam. AAR produces concrete expansion and generally leads to a loss of both strength and stiffness due to the cracking. That creates undesirable deformations, disturbances in the equilibrium of internal forces, and affects the operability and safety of dams. In this work, we develop the real case of predicting the Song Loulou spillway's gate damage by both modeling a spillway's pier and implementing a methodology in Cast3M. The loss of functionality considered here is jamming of the spillway's gate due to the deformations induced by AAR, which is one of the most dangerous disorder impacting negatively the dam on all the other assets. First of all, we present a brief review of chemo-physical processes that control the structural behaviour of concrete dams suffering from AAR. In a second step, we make a summary of the simplified methodology for recalculating an AAR affected structure proposed by the IFSTTAR in the technical guide for internal swelling reaction affecting structures management support. It is mainly based on damage law proposed by Larive, works by Ulm and his collaborators, and model suggested by Li and Coussy. Thirdly, we indicate the collected and processed data (geometry, material properties, loads, temperature and relative humidity) for our case study. Computations performed with Cast3M predict the date of occurrence of the spillway's gate's blocking due to AAR. Although this work might be used as a maintenance management tool of the Song Loulou AAR affected hydropower dam, it would be more efficient to consider the effect of uncertainties affecting the input data and the model parameters. Probabilistic approaches, reliability analysis in particular, will be used to address this problem in a further work.

Keywords: Structural damage, prediction, alkali-aggregate reaction (AAR), concrete dam, Cast3M.

Sub-themes:

√ Advances in Modeling of Structures (AMS)

 Materials for Construction (MFC)

 Innovative Design and Methods in Construction (IDM)

 Geotechnics for Environment and Energy (GEE)

1. Introduction

AAR is a deleterious chemical reaction which occurs in concrete between the highly alkaline cement paste and non-crystalline silica (silicon di-oxide), which is found in many common aggregates and/or dissolved within aggregates. The reaction produces a hydrophilic gel which Dent Glasser & Kataoka (1981) explanation of the formation mechanism, supplemented by Poole (1992) was adopted by the majority of the civil engineering scientific community. Concrete expansion induced by the gel may cause local micro-cracking with consequent degradation of elastic properties and material strength. Many models have been proposed to evaluate the material and structure degradation due to AAR. Although there is a considerable number of AAR models and even classification of these in the literature, they can be regrouped into two large families: models to describe the observations from the aggregate to the core scale and those aiming to address the observations at the structure level. The first family, made up of microscopic and mesoscopic models, evaluate AAR local effects through the description of chemo-physical mechanisms. Unfortunately, they are not yet able to be used for AAR affected structure assessment. For that purpose, we can use some of the models of the second family called macroscopic models. They evaluate AAR global mechanical effects on affected structures based on macroscopic observations and environmental data. Most of them are first calibrated and validated on the basis of experimental data provided by accelerated laboratory tests of Larive (1998) and Multon (2004). One of the oldest of them, Charlwood (1994) and Thompson *et al.* (1994) proposed to consider, within the thermal equivalence approach, an anisotropic gel expansion, driven in a phenomenological way by the local principal stresses. Then from Huang & Pietruszczak (1996), the models of this family have been developed considering the adequacy between the couple (ASR kinetics / mechanical constitutive law) and the effects of ASR on the structure. In some case, they are strongly coupled (evolution of the constitutive law in parallel to the swelling kinetics of gel via the pressure); in others, there is a weak coupling (superposition of the mechanical stress to the stress induced by gel expansion). The considered mechanical constitutive laws vary from linear elastic hypothesis to isotropic damage, even anisotropic damage.

Most of the applications of macroscopic models intended to assess AAR affected dam damage: Léger *et al.* (1996), Fairbairn *et al.* (2006), Comi *et al.* (2009), Bourdarot *et al.* (2010), Altarejos-García *et al.* (2012), Pan *et al.* (2013). However, none of them assessed the dam behavior for a functional failure mode, which is our case here.

In this study, we develop the real case of predicting the Song Loulou spillway's gate damage by both modeling a spillway's pier and implementing the LCPC (2003) methodology in Cast3M (2014). The loss of functionality considered here is jamming of the spillway's gate due to the deformations induced by AAR, which is one of the most dangerous disorder for that hydropower dam since it has a negative impact (overload risk) on all the other assets. Li & Coussy (2002) model, a weak coupling macroscopic model, is the one used here.

2. LCPC ASR affected structure assessment methodology

Here, we make a summary of the simplified methodology for recalculating an AAR affected structure proposed by IFSTTAR, LCPC (2003), in the technical guide for internal swelling reaction affected structures management support.

2.1. The methodology main steps

The methodology different phases, steps, and corresponding equations are presented in Table 1.

Table 1. LCPC (2003) ASR affected structure assessment main steps

Phases	Steps	Equations
a. Data collection	i. Structure measurement	Cracking Index (CI): $d_s(t) \quad t_0^s \leq t \leq t_1^s$
	ii. Concrete core expansion Test ($\theta_{res} = 38°C, h_{res} = 100\%$)	$\varepsilon_c(t) = \begin{cases} unknown & 0 \leq t \leq t_0^c \\ \varepsilon_c(t_0^c) + \varepsilon_{res}(t) & t_0^c < t \leq t_1^c \end{cases}$
	iii. Thermo-hydrometric conditions investigation	$\theta_s(x,t), h_s(x,t) \quad 0 \leq t, \quad (x \in \Omega)$
b. Data analysis	iv. Structure thermo-hydrometric computation	$\begin{cases} d_s(t) & t_0^s \leq t \leq t_1^s \\ \theta_s(x,t), h_s(x,t) \quad 0 \leq t, & (x \in \Omega) \end{cases}$
	v. Core thermo-hydrometric conditions	$\vartheta_c(t), h_c(t) = \begin{cases} \theta_s(x_c,t), h_s(x_c,t) & 0 \leq t \leq t_0^c \\ \theta_{res}, h_{res} & t_0^c < t \leq t_1^c \end{cases}$
c. Model calibration	vi. Core level calibration	$[\varepsilon_0^{\infty}, \tau_c^0, \tau_L^0]^{(k)}, \varepsilon_c^{0,(k)}, k = 1 \ldots n$ (n=10)
	vii. Structure level calibration	$\left[[\varepsilon_0^{\infty}, \tau_c^0, \tau_L^0]^{(k)}, \varepsilon_c^{0,(k)}\right] / d_s^{cal,(k)}(t) \approx d_s(t)$
d. Study of the structure	viii. Structural numerical evaluation	Li & Coussy (2002) model
	ix. prediction of ASR effects	

Where: $d_s(t)$ is the cracks opening distance (width), $t_{0,1}$ is a period starting/ending time respectively, "s" in lower or upper index indicate something relate to the structure, "c" in lower or upper index indicate something relate to the core, $\varepsilon_0^{\infty} = \beta_0$ is the AAR expansion coefficient, τ_c^0 is the characteristic time at 38 °C, τ_L^0 is latency time at 38 °C.

The algorithm of this methodology can be found in Li & Coussy (2004) appendix.

2.2. Li & Coussy (2002) model rewriting for its Cast3M implementation

Li & Coussy (2002) have proposed a chemo-mechanical approach to characterize ASR process in concrete by using a normalized reaction extent $\xi \in [0,1]$, where $\xi = 0$ represents no formation of ASR gel, while $\xi = 1$ stands for the exhaustion of reactants. It gives both the constitutive relation of the affected concrete and the evolution law for ASR gel formation:

$$\begin{cases} \sigma_{ij} = \left(K - \frac{2}{3}G\right)(\epsilon_{kk} - \epsilon_{kk}^p)\delta_{ij} + 2G(\epsilon_{ij} - \epsilon_{ij}^p) - 3\beta K \xi \delta_{ij} \\ t_c \dot{\xi} = 1 - \xi \end{cases}$$

where σ_{ij}, ϵ_{ij}, and ϵ_{ij}^p stand for the components of the material stress, total strain, and plastic strain tensors, respectively; K and G are the overall bulk and shear moduli, respectively, β represents ASR expansion coefficient, and t_c is the ASR characteristic time. K and G can be express in term of Young modulus and Poisson coefficient as :

$$K = \frac{E}{3(1-2\nu)}, \quad G = \frac{E}{2(1+\nu)}$$

By replacing them in σ_{ij} and after simplification, we have:

$$\sigma_{ij}(t,T(t)) = \frac{\nu E}{(1-2\nu)(1+\nu)}(\epsilon_{kk} - \epsilon_{kk}^{p})\delta_{ij} + \frac{E}{1+\nu}(\epsilon_{ij} - \epsilon_{ij}^{p}) - \frac{E}{1-2\nu}\beta\xi(t,T(t))\delta_{ij}$$

The expression of $\xi(t,T)$ (the effect of relative humidity can be neglected here) given in Saouma (2014) is:

$$\xi(t,T(t)) = \frac{1 - e^{-\frac{t}{\tau_c(T(t))}}}{1 + e^{-\frac{(t-\tau_L(T(t)))}{\tau_c(T(t))}}}$$

Where $\tau_{c,L}(T(t))$ are given from Ulm *et al.* (2000):

$$\tau_{c,L}(T(t)) = \tau_{c,L}(T_0)e^{\left[U_{c,L}\left(\frac{1}{T(t)} - \frac{1}{T_0}\right)\right]}$$

With: $T_0 = 38°C = 311°K$ (Temperature of the LCP N°44 test), $U_c = 5400 \pm 500K$ and $U_L = 9400 \pm 500K$

3. Case study: Song Loulou spillway's gate damage due to pier swelling

Before presenting the results we obtained for the prediction of the date of occurrence of the spillway's gate's blocking due to AAR, we present the geometry of the pier modeled on Cast3M, we indicate the collected and processed material and environmental data we used (a few of them can be found in Guillemot *et al.* (2013)), we also point out the maximum AAR expansion's displacement of the pier to avoid the tainter gate blocking.

3.1. Spillway's pier modeling in Cast3M

As we can see from Le Fichou (2011), making a Finite Element Analysis (FEA) with Cast3M implies to follow the flowchart on Figure 1.

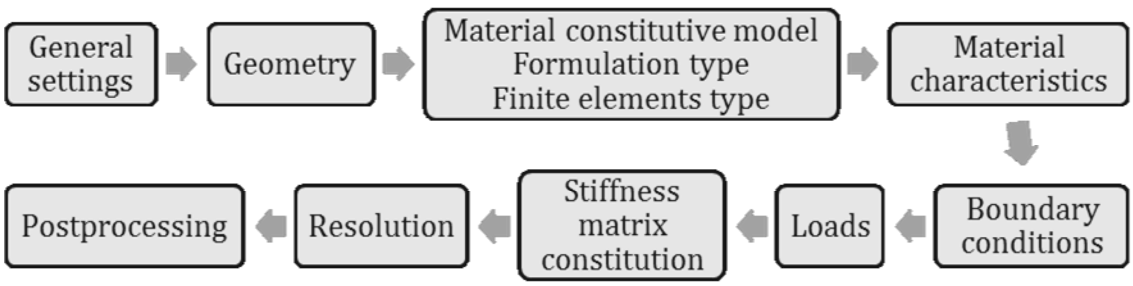

Figure 1. Flowchart of a Finite Element Analysis with Cast3M

The geometry of the pier has been divided into basic volumes such that adjacent volumes always have an identical common surface. The points used in the construction of these basic volumes were defined in the clockwise direction. The number of finite elements and mesh size are parameterized in order to tailor precision of the geometry according to the results of AAR modeling. Figure 2 represent the entire pier built in Cast3M. Meshing has been achieved with cub8 and in way to be more refined on the pier lateral skin.

We made the hypothesis that our pier has an elastic behavior, and by doing an analogy with a combination of both the Hooke-Duhamel Law and the Gabriel-Lamé Law, we implement Li &

Coussy (2002) model on Cast3M with the model “MECANIQUE ELASTIQUE ISOTROPE” (that include thermal expansion) in which the coefficient of thermal expansion is given by :

$$\alpha = \beta\xi(t, T(t))/(T(t) - T_0)$$

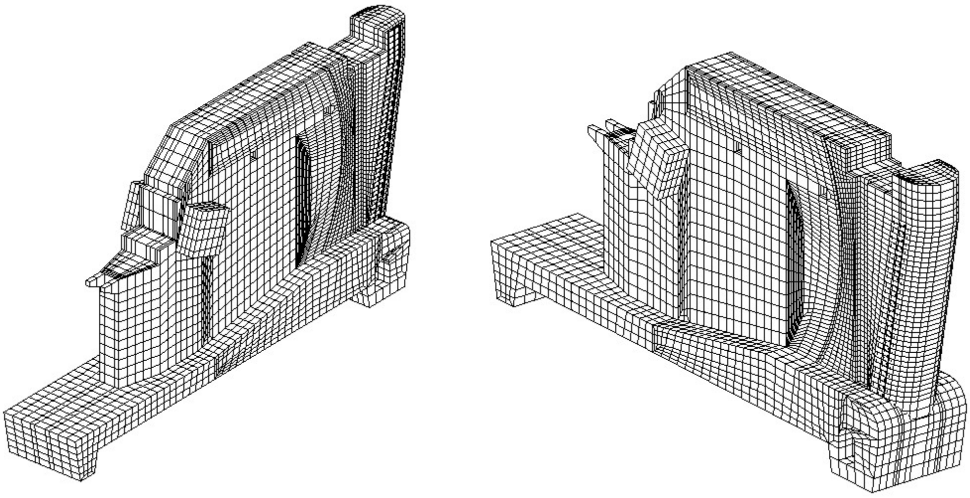

Figure 2. Song Loulou spillway’s pier Cast3M meshed model

The data for defining the material characteristics, boundary conditions, and loads are shown below.

3.2. AAR information and model calibration

Table 2 present both the collected and processed material and environmental data we used, and the model parameters we obtained after calibration.

Table 2. Thermo-chemo-mechanical parameters for the Song Loulou spillway’s pier assessment

Parameter	Symbol	Unit	Value
Young’s modulus of concrete	E_C	GPa	16
Poisson’s ratio of concrete	ν	-	0.2
Mass density of concrete	ρ_C	Kg/m^3	240
Compressive strength of concrete	R_c	MPa	15
Tensile strength of concrete	R_t	MPa	2.5
Tensile strength of steel	R_s	MPa	240
Young’s modulus of steel	E_s	GPa	200
Characteristic time	τ_c^0	d	912
Latency time	τ_L^0	d	1 277
AAR expansion coefficient	β_0	%	4.5.10^{-3}
Ambient temperature	θ_{atp}	°C	24.9-28.3
Humidity of concrete	h_s	%	78-94
Sluicegate load on pier’s console	p_{slpc}	MPa	3.144
Hydrostatic load on the front of the pier	p_{hlfp}	MPa	0-0.190

Figure 3 shows the monthly minimum, mean, and maximum values of the Song Loulou atmospheric temperature for the period from 1975 to 2008.

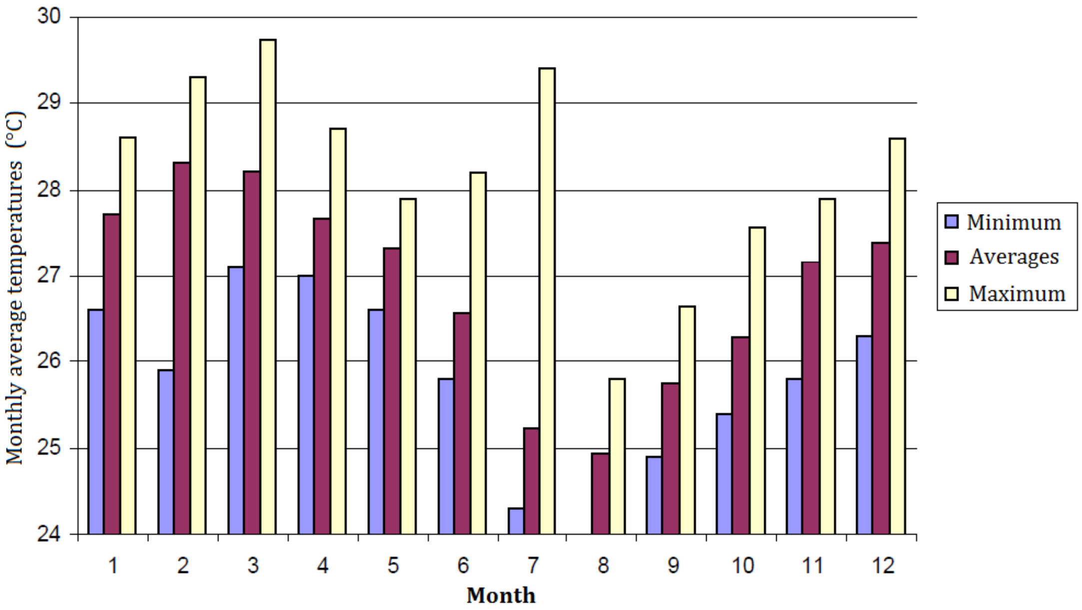

Figure 3. Monthly Song Loulou atmospheric temperature from 1975 to 2008

3.3. Maximum AAR expansion's authorized displacement Dmax

The maximum AAR expansion's authorized displacement corresponds to the maximum lateral clearance Dmax for the spillway's tainter gate to slide correctly, presented on Figure 4.

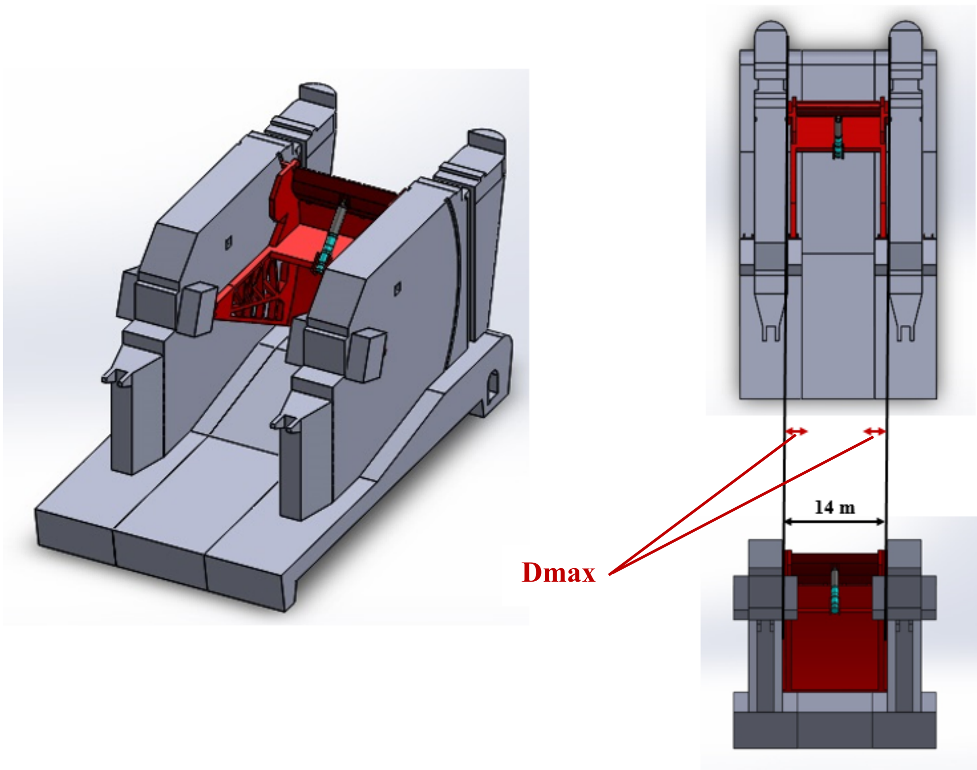

Figure 4. Song Loulou spillway's tainter gate lateral clearance

The value indicated by the spillway's supervisor for the maximum lateral clearance is: **Dmax = 40mm**. We should point out the fact that this value is true for each of the two piers involved regardless of the other one state.

3.4. Prediction of the date of occurrence of the spillway's gate's blocking due to AAR

We solve our case in Cast3M by implementing the data and model presented above. The principal results we obtained are presented below.

3.4.1. Spillway's pier behavior evaluation

The Song Loulou spillway has eight piers for seven tainter gates. We choose the second pier from the left to the right with respect to the flow direction for our case study. Figure 5 present the pier deformation after 2500 days (in cyan) and 6000 days (in yellow) respectively, with a same amplification factor for the two and the initial state in black.

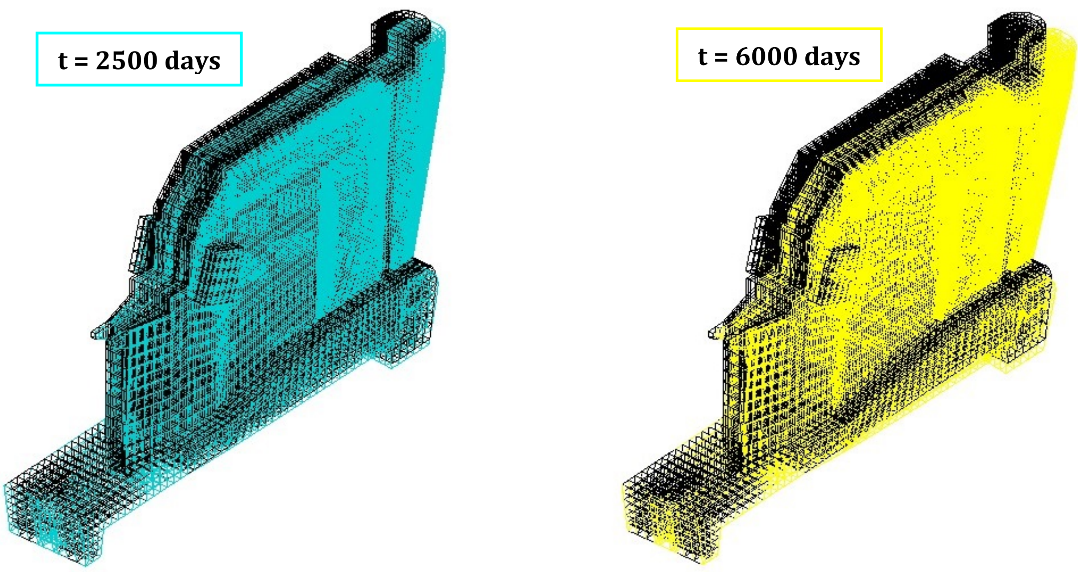

Figure 5. Pier deformation after 2500 days and 6000 days respectively

As we can see on Figure 5, the pier's lateral displacement to the left, with respect to the flow direction, grows with time.

3.4.2. Determination of the day of failure Df

The day of failure corresponds to the time in day when the pier's maximum lateral displacement is equal 40mm, namely: **Df = 6947 days**.

4. Conclusion

Calculations performed with Cast3M predict that the spillway's gate's blocks due to AAR after 6947 days. Although this work might be used as a maintenance management tool of the Song Loulou AAR affected hydropower dam, it would be more efficient to consider the effect of uncertainties affecting the input data and the model parameters. Probabilistic approaches, reliability analysis in particular, will be used to address this problem in a further work.

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