

# **ALKALI AGGREGATE REACTIONS IN DAMS; Stress Analysis and Long Term Predictions**

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## **ABSTRACT**

This three part paper presents a constitutive model for alkali-aggregate reactions (AAR) in structures, a parametric study to assess this model, and finally its application to an actual 3D structure. The model is deeply rooted in the physics, chemistry and mechanics of the reaction, and accounts in a rational and non-empirical manner for most of the known effects on and of AAR. The model is implemented in a finite element code, validated and assessed through an extensive parametric study. Finally, the model is used to assess the long term response of an arch gravity dam. These tasks are greatly facilitated by the full automation of the data preparation process (which includes transient thermal analyses, histograms of pool elevations, and other time dependent characterization). Finally modern system identification techniques are used to automatically determine the optimum set of AAR parameters which provide the best fit between numerical model and field data from dam construction to present.

## **INTRODUCTION**

An alkali-Aggregate reaction in dams has been extensively investigated from a strictly material point of view. Yet, once it was determined that AAR is present, those investigations are of little help to assist the dam owner on what are the implications on the overall structural response of the dam. This paper seeks to provide an answer to that most fundamental question “so what?”

Many old concrete structures are known to suffer from Alkali-Aggregate Reactions (AAR). This internal reaction causes gel formation inside the aggregate, and results in swelling of the concrete. This swelling in turn may cause secondary compressive stresses (if the structure is restrained, as most are), localized map cracks, and ultimately structural cracks. In addition, the concrete tensile strength and Elastic modulus are likely to significantly decrease. One or a combination of these effects can cause major concern for massive concrete structures such as dams. Indeed, many dams worldwide are known to suffer from this reaction, for which there are no known effective remedies. Sealing the upstream face will only slow the swelling (though only marginally), and cutting the dam to relieve the stress build-up is only addressing the symptoms of the problem and not its causes. Indeed this is a major problem, and at best one can attempt to make realistic long term predictions as to extent of AAR induced deformation and damage.

Saouma and Perotti (2005) have recently developed a comprehensive constitutive model for AAR in concrete. This coupled chemo-thermo-mechanical formulation was largely inspired by the extensive experimental research undertaken at the *Laboratoire Central des Ponts et Chaussées* by Larive (1998) and Multon (2004). Though thoroughly tested at the constitutive level for simple geometries, the model was not yet applied to the practical analysis of a dam.

This paper will then: 1) Develop a rigorous methodology for modeling AAR in dams through a finite element code with a constitutive model which seems to capture most of the physics and chemistry of the reaction; 2) Describe an extensive parametric study on the proposed model as applied to a 2D dam model to address some fundamental questions; and 3) Describe the comprehensive 3D analysis of an actual arch-gravity dam.

## **BACKGROUND**

### **AAR in Dams**

Numerous dams worldwide are known to suffer from AAR. Whereas it would be impossible to list them all here, the web site of ACRES (2005-a) provide a good overview.

The Tennessee Valley Authority (TVA) has three major projects are experiencing AAR, including Fontana Dam and Powerhouse, Hiwassee Dam and Powerhouse, and Chickamauga Lock, Dam and Powerhouse (Wagner and Newell, 1995). All of these dams are more than 60 years old and are experiencing problems in one or more locations due to AAR with no indication of any slowing of the concrete growth process. Some of the cracks were 0.5 inch width by 1980.

Beltzville dam intake tower (170 ft tall) in Pennsylvania was constructed in the late 1960's and the reservoir was filled by 1971. During the mid 1970's, leakage from many cracks in concrete was reported in the tower, and the cracks were diagnosed as the result of AAR of the concrete. Since then, many experimental studies have been conducted on the concrete, and five repair methods have been applied on the structure (Murtaugh 1995).

Probably the most "famous" example of AAR affected dam is Mactaquac dam. Evidence of distress in the concrete structures at Mactaquac was first noticed in the mid-1970 by the increasing opening of a longitudinal vertical contraction joint in the powerhouse substructure (Gilks & Curtis 2003). By the early 1980's, leakage through horizontal construction joints in the spillway, intake and diversion sluiceway structures was also evident.

Canning Dam, is a 66 m high concrete gravity dam with a curved crest. An upward movement of 18.3 mm and lateral upstream movement of 14.2 mm were observed over the past 15 years due to AAR. Repair work was conducted, in which the section above the floor of the upper gallery level was removed, and a new reinforced concrete section was constructed to act as head beam for post-tensioning of the rest of the dam wall (Shayan et al. 2000, Sinclair 2003).

Chambon is probably the most notorious example of AAR in France. It is an 88 m high gravity dam built in the early 30's. Irreversible displacements appeared about 25 years after at a rate of about 5 mm/year in the upstream direction, and the crest moves upward by up to 3.6 mm/year. It is estimated that AAR induced swelling varies from 10 to 80 microstrain per year. Remedies included injection of

the cracks, placement of a 2.5 mm geomembrane, and cutting by an 11mm wire to reduce the initial longitudinal compressive stress estimated at 5 MPa. Cutting was carefully planned and executed in three phases. It appears that the once thought to be irreversible effects have now drastically been reduced.

Jabarooti and Golabtoonchi (2003) reported that AAR is mostly present in South-East Iran. Accelerated expansion tests (ASTM C1293) are reported (resulting in a maximum expansion of 0.45% in 28 days).

One of the first Italian dams reported to exhibit AAR is Pian Telesio which is an 80 m high arch gravity dam. This dam was one of the workbench problems assigned by ICOLD (2001).

In Portugal, Pracana dam is reported to suffer from AAR (Portugese National Committee on Large Dams, 2003). This is a 60 m high concrete gravity buttress dam built in 1948-1951. The dam operation was interrupted in 1980 to address safety concerns. The upstream face had exhibited numerous vertical and horizontal cracks, extensive cracks in the downstream face. 80% of the cracks had an opening that was smaller than 0.5 mm, yet much leakage was noticed. After 23 years in existence, swelling amounting to 260 micro-strains was measured, and an irreversible downstream displacement of 1.2 mm/year was noticed. Treatment mainly consisted of: 1) cement grouting of cracks with an opening larger than 0.5 mm and epoxy resin grouting of all other cracks; 2) waterproofing of the upstream face using a 2.5 mm thick PVC membrane and a 1.5 mm thick geotextile (500 g/m<sup>2</sup>).

Malla and Wieland (1999) report the analysis of an arch gravity dam in Switzerland. Using the thermal equivalency method (and a most interesting, powerful and simple method to estimate the concrete internal temperature), the authors achieve an excellent correlation with measured crest displacements.

### **State of the Art and State of the Practice in AAR Modeling**

With regard to structural analysis of AAR affected structures, one must differentiate between the State of the Art and the State of the Practice. With regard to the former, there are many contenders, most of them relatively sophisticated models developed and used in the context of academic research: Huang, & Pietruszczak (1999), Ulm et al. (2000), Li (2002), Gomes, Batista and Oliveira (2004) and Bangert, et al. (2004). All of these models have a kinetics model to account for the time dependency of the reaction, and most of them are based on a tight coupling between the chemical, thermal, hygral and mechanical components. Finally, the authors have recently proposed a model (Saouma & Perotti, 2005).

On the other hand, the State of the Practice appears to be based on an early (actually one of the first) AAR model proposed by Charlwood et al. (1992) and Thompson et al. (1994). Computer programs based on these early models, Acres (2005-b) have been extensively used for major dam investigations. This early model accounted for the reduction of AAR expansion under compressive stresses, and had no kinetics component.

## **CONSTITUTIVE MODEL**

### **Kinetics Model of the Volumetric Strain**

The theoretical underpinning of the model used in this paper has been presented by the authors separately, Saouma & Perotti (2005).

The AAR expansion is considered to be a volumetric one, which rate is given by the following function

$$\dot{\varepsilon}_{vol}^{AAR}(t) = \Gamma_t(f'_t, \sigma_I) \Gamma_c(\bar{\sigma}, f'_c) f(h) \dot{\xi}(t, \theta) \varepsilon^\infty|_{\theta=\theta_0}$$

where  $\varepsilon^\infty|_{\theta=\theta_0}$  is the final volumetric expansion as determined from laboratory tests at temperature  $\theta_0$ .  $0 \leq \Gamma_t \leq 1$  is a parameter which reduces the expansion in the presence of large tensile stresses (macrocracks absorbing the gel),  $f'_t$  the tensile strength,  $\sigma_I$  the major (tensile) principal stress. Similarly,  $0 \leq \Gamma_c \leq 1$  is a parameter which reduces the AAR volumetric expansion under compression due to the possible presence of microcracks,  $\bar{\sigma}, f'_c$  are the hydrostatic stress, and the compressive strength of the concrete.  $0 \leq f(h) \leq 1$  is a function of the humidity (full expansion if it is above 80%, no expansion below 40%, partial expansion in-between),  $\dot{\xi}(t, \theta)$  the kinetics law given by

$$\xi(t, \theta) = \frac{1 - e^{-\frac{t}{\tau_c(\theta)}}}{1 + e^{-\frac{t - \tau_L(\theta, I_\sigma, f'_c)}{\tau_c(\theta)}}}$$

which is represented by the “sigmoid” curve Figure 1. Also shown is the effect of temperature on the AAR expansion. The colder the temperature, the slower the reaction (which has serious implications in the analysis of the dam where there can be a severe temperature gradient across the dam with a seasonal variation).

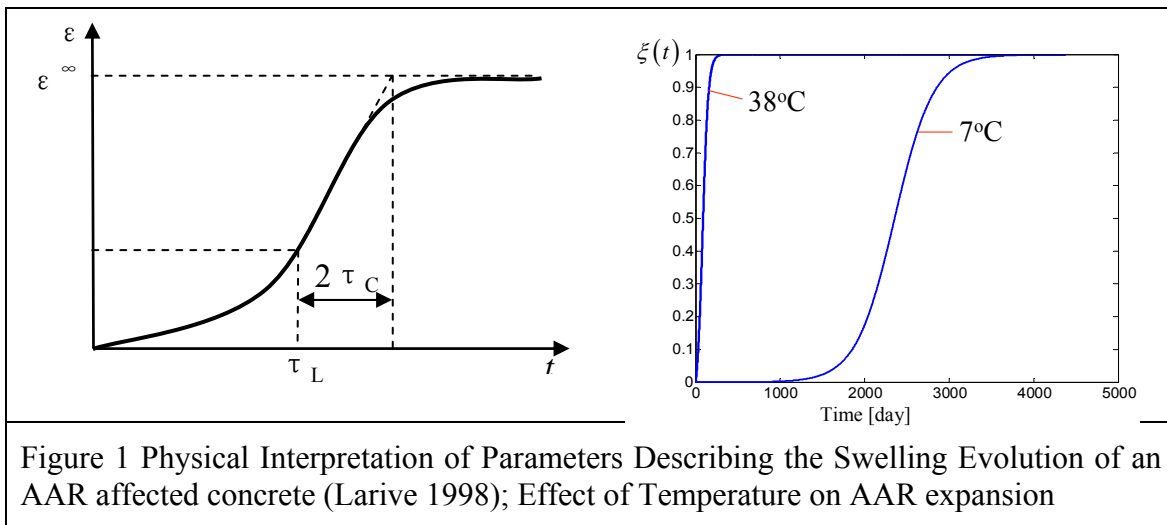


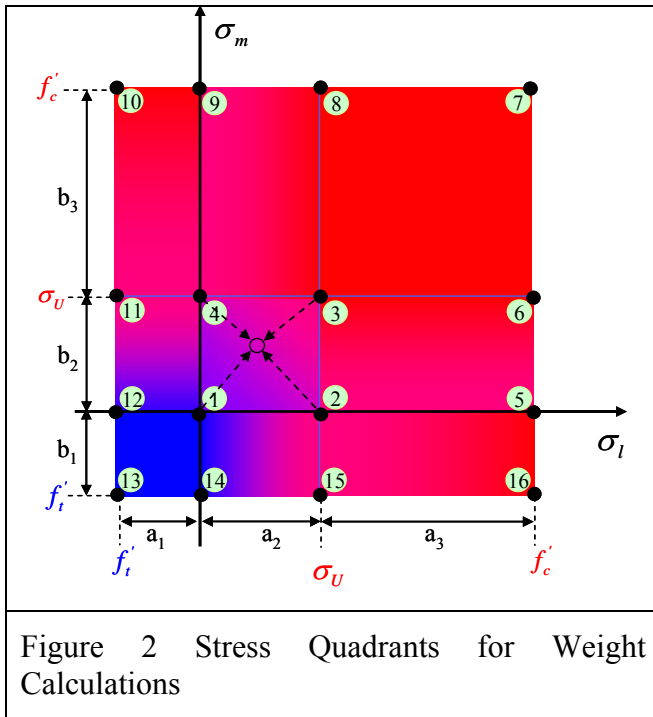
Figure 1 Physical Interpretation of Parameters Describing the Swelling Evolution of an AAR affected concrete (Larive 1998); Effect of Temperature on AAR expansion

The latency time  $\tau_{lat}$  and characteristic times,  $\tau_{car}$  are given by

$$\begin{cases} \tau_c(\theta) = \tau_c(\theta_0) \exp\left[U_c \left(\frac{1}{\theta} - \frac{1}{\theta_0}\right)\right] \\ \tau_L(\theta, I_\sigma, f'_c) = f(I_\sigma, f'_c) \tau_L(\theta_0) \exp\left[U_L \left(\frac{1}{\theta} - \frac{1}{\theta_0}\right)\right] \end{cases}$$

where  $\theta$  is the current temperature,  $\tau_L(\theta_0)$  and  $\tau_C(\theta_0)$  are the reference latency and characteristic times measures in the laboratory at temperature  $\theta_0$ .  $I_\sigma, f'_c$  are the first stress invariant and the concrete

compressive strength respectively. Finally,  $U_L$  and  $U_C$  are the activation energies for the latency and characteristic times.



### AAR Volumetric Strain Redistribution

Once the volumetric AAR strain is determined, it is decomposed into a tensorial strain in accordance to the three weight factors associated with the principal stresses (Saouma & Perotti 2005). First we compute the principal stress tensor vector  $[\sigma_k \ \sigma_l \ \sigma_m]$ , and then we seek to compute each of the three weights  $[W_k \ W_l \ W_m]$  and then the volumetric AAR strain will be given by

$$\epsilon_i^{AAR} = \frac{W_i}{W_k + W_l + W_m} \epsilon_{Vol}^{AAR}$$

Thus we need to determine  $W_i$ . Considering  $W_k$ , this will be computed from

$$W = N_1 W_1 + N_2 W_2 + N_3 W_3 + N_4 W_4; \quad \begin{cases} N_1 \\ N_2 \\ N_3 \\ N_4 \end{cases} = \frac{1}{ab} \begin{cases} (a - \sigma_l)(b - \sigma_m) \\ \sigma_l(b - \sigma_m) \\ \sigma_l \sigma_m \\ (a - \sigma_l)\sigma_m \end{cases}$$

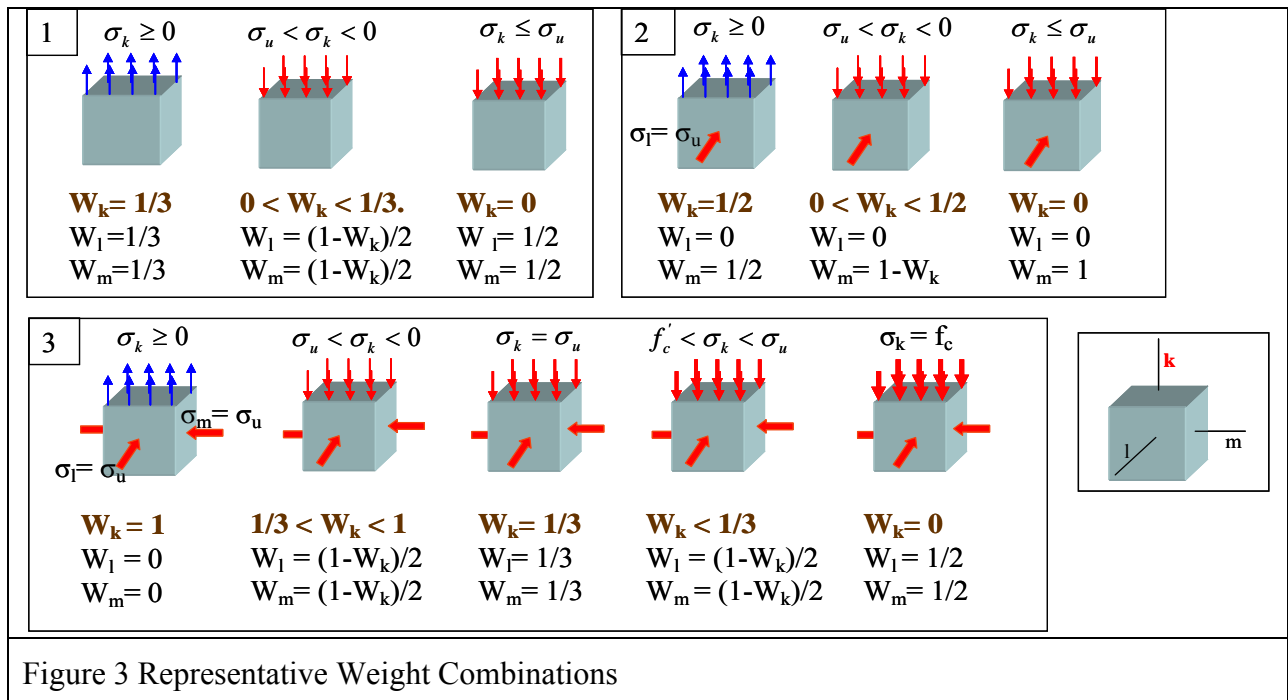


Figure 3 Representative Weight Combinations

where a and b are the dimensions of an “element” size in the stress plot of Figure 2 which is expressed in terms of the tensile strength, compressive strength, and an upper uniaxial compressive stress beyond which no AAR expansion occurs. A weight is given to each of those nodes (Saouma & Perotti 2005). Using this approach, we obtain the weights shown in Figure 3.

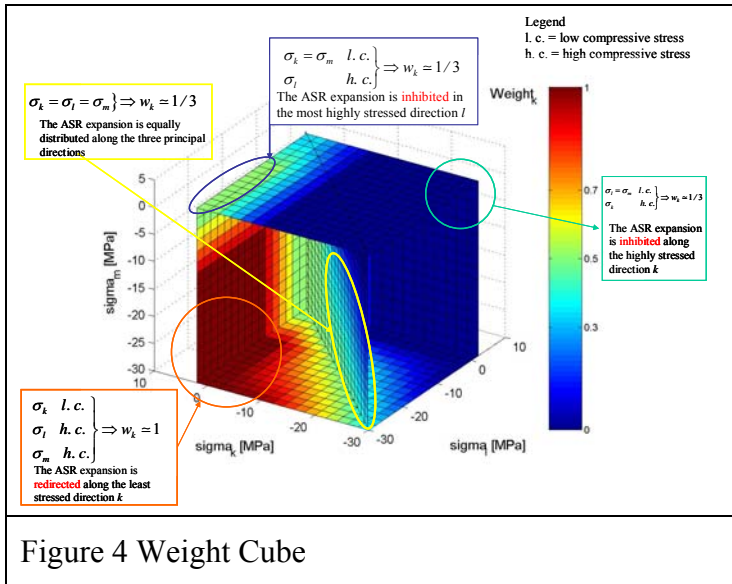


Figure 4 is an illustration of the weight distribution in the 3D principal stress space.

Accompanying AAR expansion there is usually a reduction in the tensile strength and the Young’s modulus. We assume that the temporal degradation of those two parameters is given by

$$E = E_0 [1 - (1 - \beta_E) \xi(t, \theta)]; f_t = f_{t,0} [1 - (1 - \beta_f) \xi(t, \theta)]$$

Where  $\xi(t, \theta)$  is the same kinetic equation previously defined. This degradation model is shown in Figure 5.

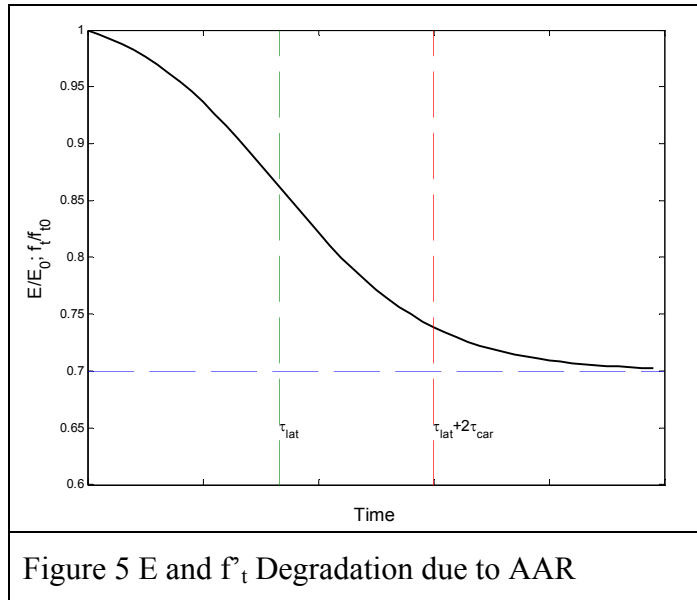


Figure 5 E and  $f_t$  Degradation due to AAR

## VALIDATION

The model and its implementation have been validated through numerous tests. One of them is the analysis of the experimental work of Multon (2004) in which AAR cylinders were subjected to a biaxial confinement, Figure 6

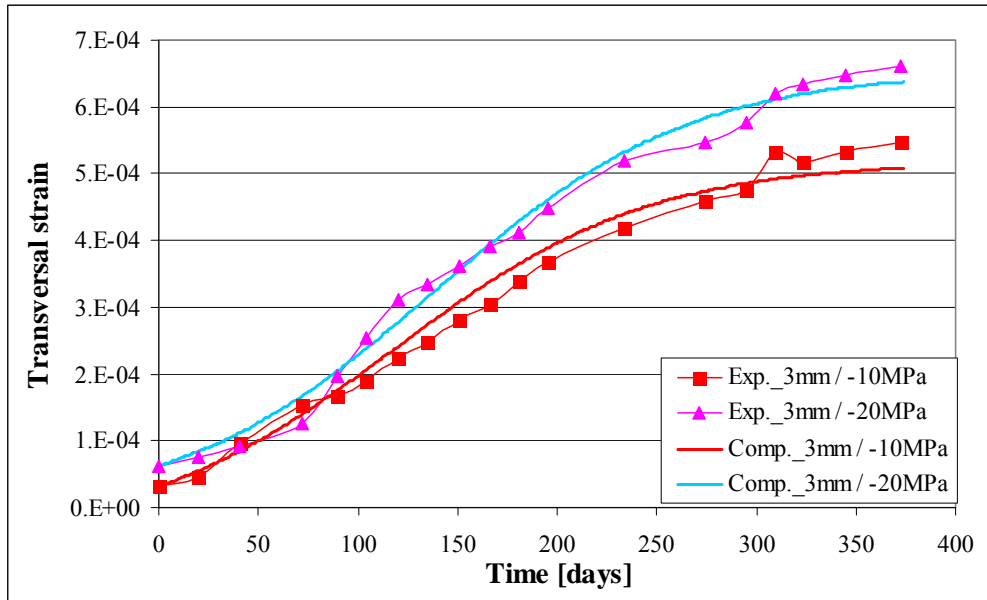


Figure 6 Validation of Model in which Experimental and Computed AAR Strains are Compared

### SYSTEM IDENTIFICATION

A particularly challenging problem in the analysis of older structures affected by AAR, is the determination of the kinetics parameters ( $\varepsilon^\infty, \tau_L(\theta_0)$  and  $\tau_C(\theta_0)$ ). The difficulty stems from the fact that one is confronted (almost by definition) with an older structures for which it is practically impossible to conduct laboratory experiment and extract an expansion curve. Hence, the structural analysis must be conducted with an initial set of assumption, results compared with the dam recorded displacements, and then input parameters updated. This labor and computation extensive procedure is prone to numerous errors and is inefficient. Accordingly, AAR problems are prime candidates for system

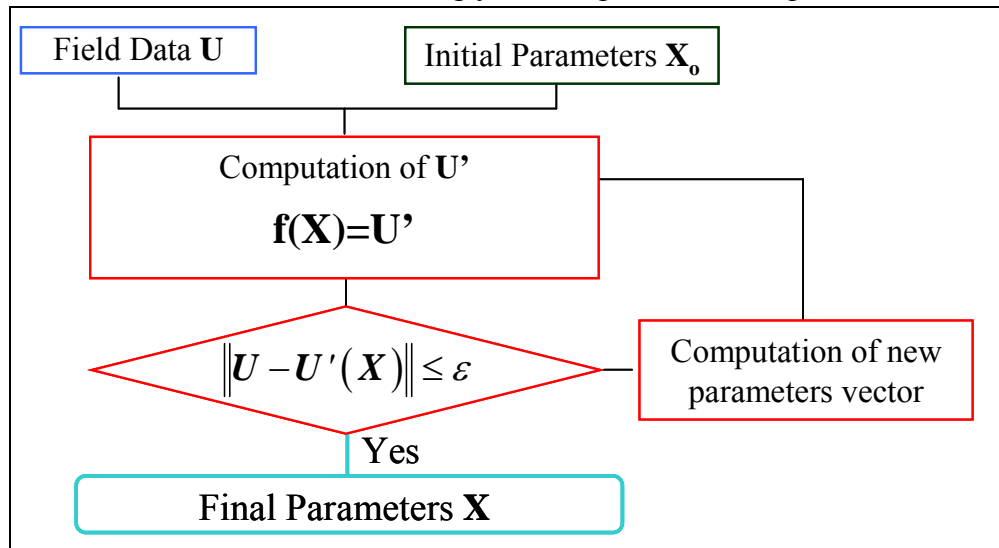
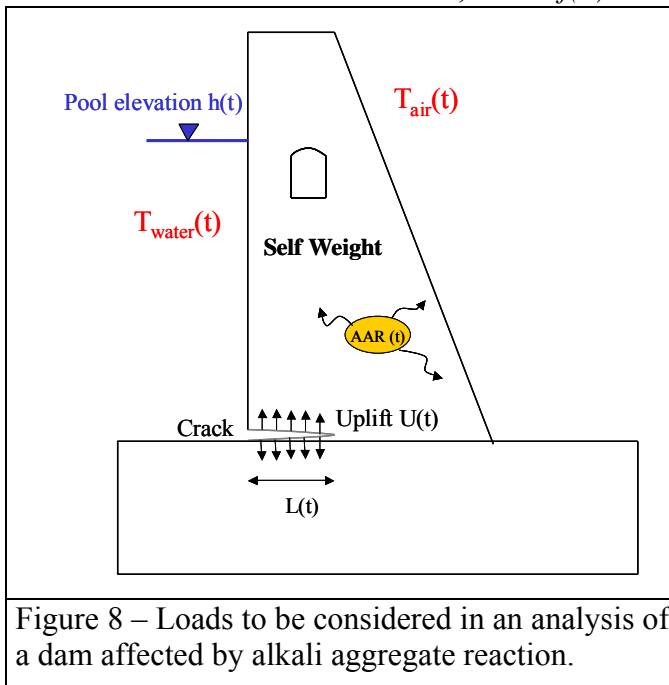


Figure 7 System identification Algorithm to Reconcile Field Crest Displacements with Numerically computed ones

identification. This will be accomplished through a special optimization program written in Matlab<sup>®</sup> which reads numerical predictions, compare them with field data, update the set of AAR parameters, re-launch the execution of the finite element code until convergence is reached, Figure 7.

## ANALYSES PROCEDURES

Internal spatial and temporal variation of: 1) the temperature (as the AAR is thermodynamically activated), and 2) stresses (to correctly redistribute the volumetric AAR strain into a tensorial one) must be determined, Figure 8. As to the humidity distribution, one can reasonably assume that inside a dam it is between 90% and 100%, hence  $f(h)=1$ . Hence, prior to a stress analysis, a transient thermal analysis must be undertaken.



### Thermal Analysis

A transient thermal analysis of the dam (without the rock base) must first be performed in order to obtain a temporal map of the internal temperature. Such analysis depends on;

1. Water temperature variation during a typical year (at least 12 or 24 increments per year). It is also necessary to know the water temperature variation along the depth of the reservoir (for dams over 50 m high)
2. Pool elevation variation during a typical year;
3. Concrete thermal properties (the necessary thermal properties depend on the complexity of the thermal analysis).
4. Grouting temperature.

Of paramount importance in this (and the stress analysis) is the definition of the Analysis Time Unit (ATU) with respect to which all material properties and time steps shall be normalized. Typically, one ATU corresponds to two weeks.

### Stress analysis

Following the thermal analysis, and prior to initiating an AAR stress analysis, one must collect the following:

- 1) Yearly variation of the nodal temperatures for a typical year from the preliminary thermal analysis;
- 2) Yearly variation of pool elevation;
- 3) Grouting or free stress reference temperature;
- 4) Elastic concrete properties;
- 5) Joints material properties;
- 6) Preliminary AAR properties to describe the temporal evolution of the alkali aggregate reaction.
- 7) Dam construction completion date.

Thus the first five increments of the analysis are devoted to the impounding of the dam, and then we cycle through all the additional loads (by increments of two weeks), Figure 9. From an implementation point of view, these data can be easily organized inside a spreadsheet, and then imported into the mesh generator Kumo.

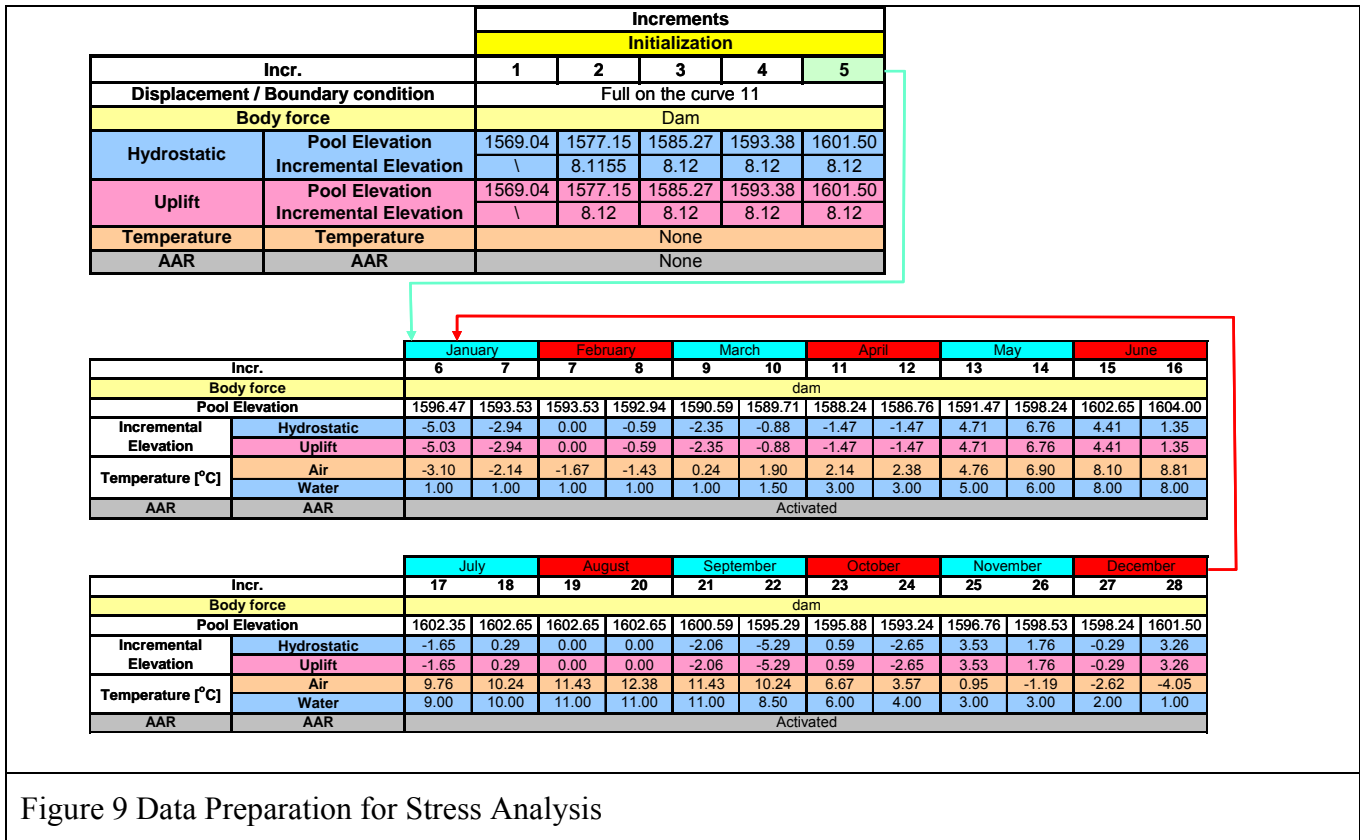


Figure 9 Data Preparation for Stress Analysis

The finite element mesh for the stress analysis of a dam affected by AAR has to be different from the one used for the thermal analysis and it includes the joints, the interface between dam and rock foundation and the rock foundation. These parts are not necessary in the thermal analysis but are very important to capture the real behavior of a dam affected by AAR. The thermal load is applied in the stress analysis by exporting the nodal temperatures of the last year from the thermal analysis. However, it should be kept in mind that:

- 1) Stress analysis requires the temperature difference with respect to the stress free temperature, namely the grouting temperature  $T(x,y,z)-T_0$ .
- 2) AAR evolution depends on the total absolute temperature inside the dam  $\theta(x,y,z)$

### Automated Analysis Procedure

Loading definition for an AAR investigation can be quite complex and error prone (unless it is fully automated). The impounding of the newly completed dam is first simulated through a few increments (about five) to allow joint adjustments in the nonlinear analysis. Following this initial phase, the analysis input data file is completed as follows. For each of the  $n$  years (typically 50), and for each of the  $m$  yearly ATU (typically 24), apply correct pool elevation (upstream and downstream), uplift

pressures and internal nodal temperatures. This can result for a 3D analysis in an input data file of about 500 MBytes.

Accordingly, our finite element preprocessor (Kumo, 2005) was extensively modified to facilitate data input, importing results from transient thermal analysis code, and of pool elevation variation from an external files. Furthermore all the data preparation is performed through greatly simplified graphical user interfaces to minimize errors, Figure 10.

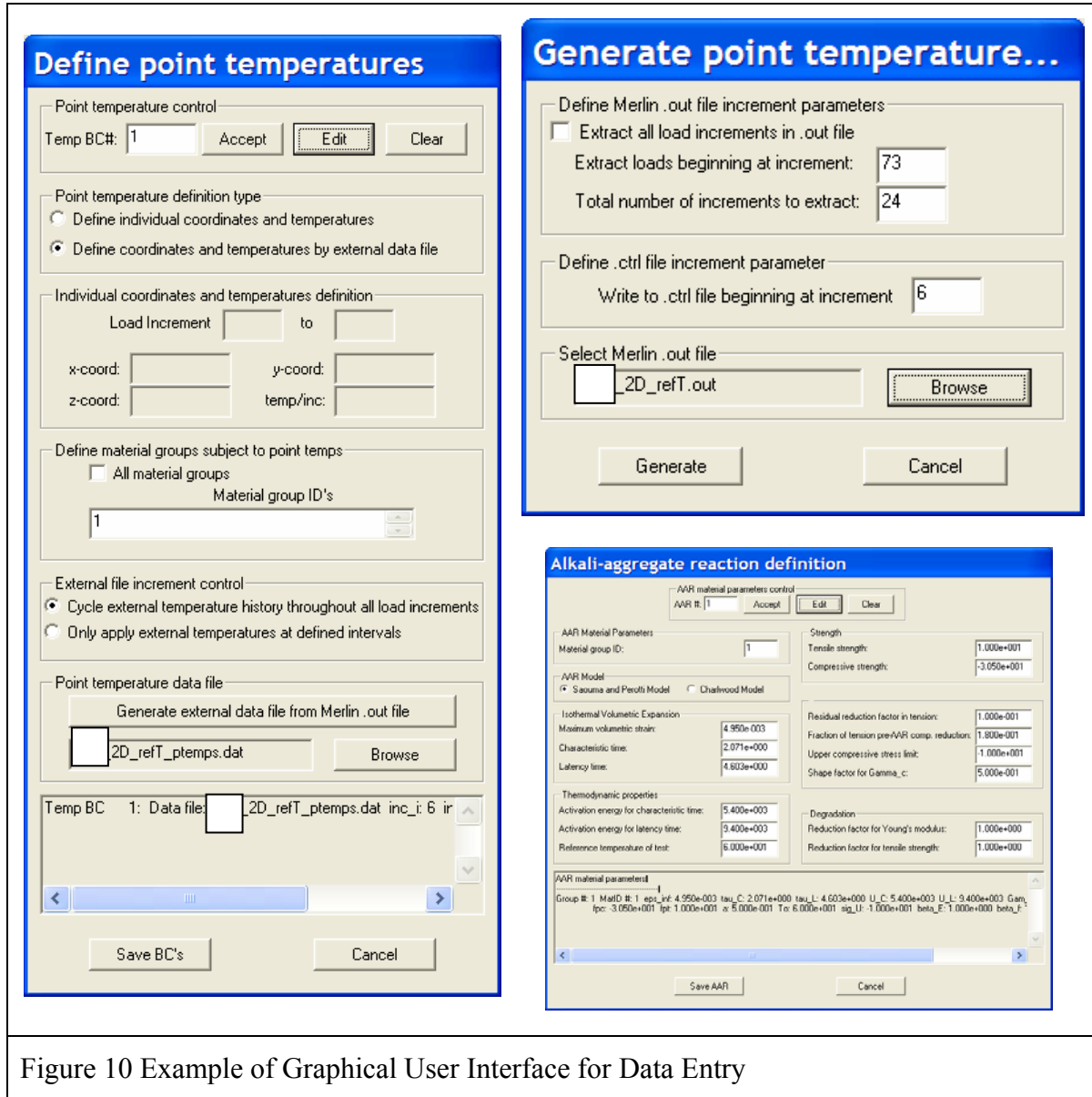
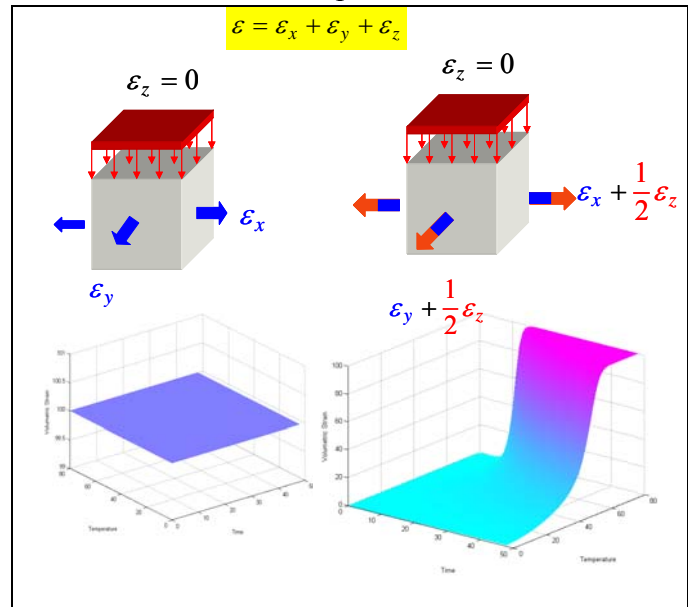
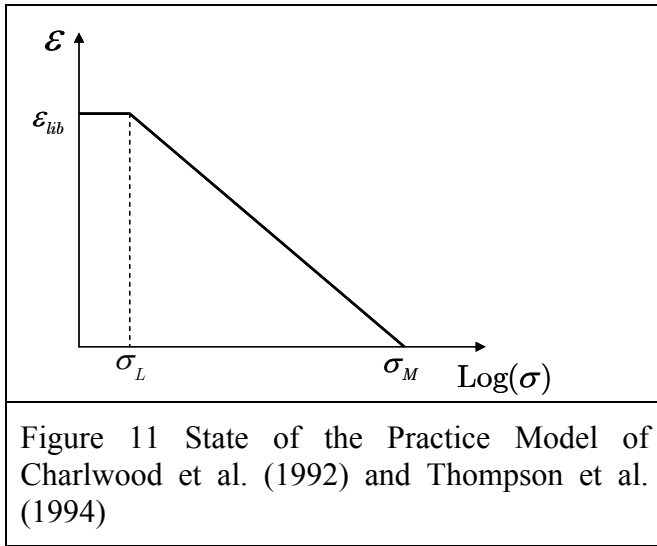


Figure 10 Example of Graphical User Interface for Data Entry

## COMPARISON WITH STATE OF THE PRACTICE

The State of the Practice is essentially based on the Model of Charlwood et al. (1992) and Thompson et al. (1994). To the best of the authors knowledge, these are the only scientific publications (in conference proceedings) upon which the State of the Practice is based. This model is essentially summarized by Figure 11 where the AAR strain is reduced from the unconfined value at  $\sigma_L$  to zero at

$\sigma_u$  according to a logarithmic scale. There is no redistribution of stresses as evidenced in the latest research, nor is there any account for temperature, nor is there a kinetic law, Figure 12. Those may have been subsequently added on an *ad-hoc* basis, but not referenced in the open literature.

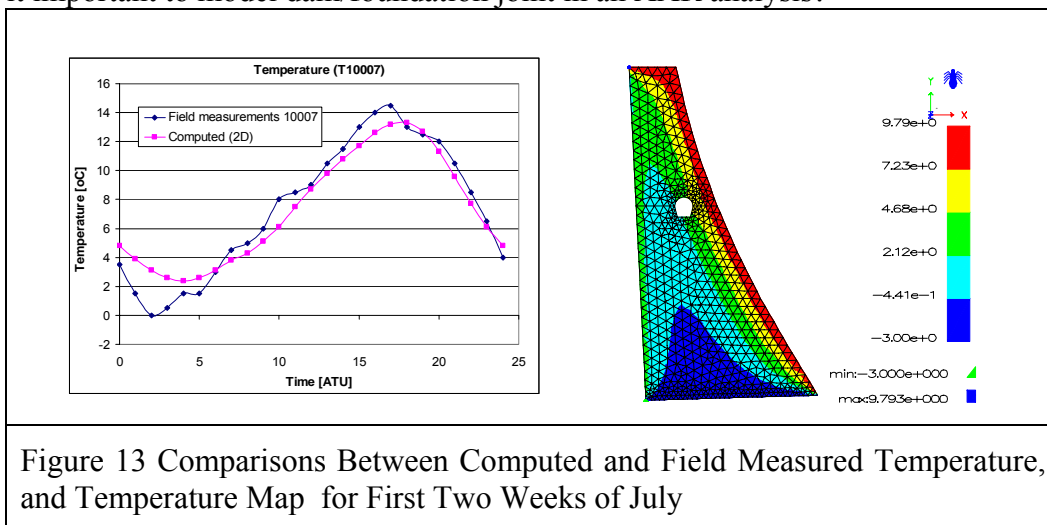


## 2D PARAMETRIC STUDY

Given the relative complexity of the analysis procedure, and prior to undertaking a 3D analysis, it was deemed desirable to perform a preliminary 2D parametric analysis to address the following questions:

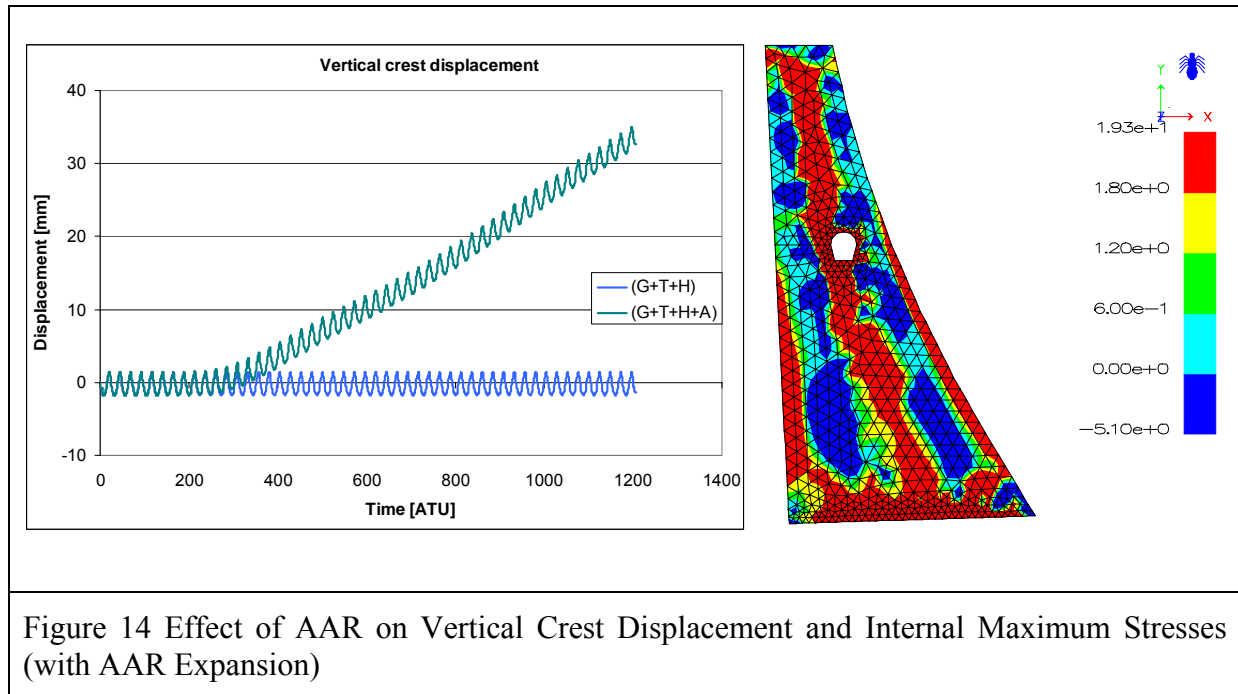
How does AAR affect the state of stress in a dam subjected to normal gravity (G), hydrostatic (H), and temperature (T) load?

1. Should we account for the seasonal variation in
  - a. Pool elevation
  - b. Temperature during a long term analysis of a dam subjected to AAR?
2. How many increments per year are necessary to obtain reliable results?
3. Is it important to model dam/foundation joint in an AAR analysis?



4. How important is it to model the sigmoid kinetics?
5. How important is the effect of concrete Young's modulus degradation?
6. It is important to model the inner and external concrete of a dam?
7. How different is our model from the one of the State of the Practice?

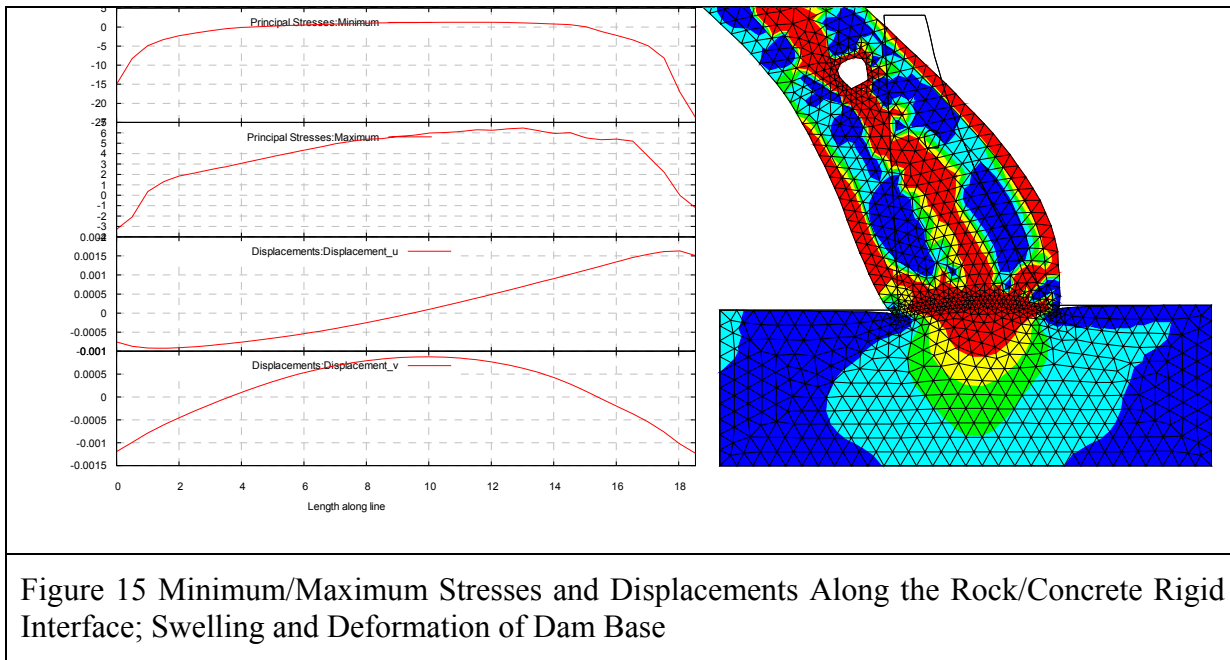
Prior to the stress analysis, a transient thermal analysis was performed, and computed temperatures compared with field measured ones, Figure 13.



**Effect of AAR:** If we first examine the effect of AAR on the both the vertical crest displacement and the internal state of stress, Figure 14, we note that indeed the analysis captured both the seasonal variation of the temperature, and the long term irreversible expansion of the dam. Equally interesting is the zone of internal high stresses inside the dam. Though there is a complex interplay between temperature, stresses and expansion, the internal core of the dam (being cooler, and thus with a reduced expansion) has its expansion constrained giving rise to some of tensile stresses. This is of particular concern, as it may potentially cause hidden (except in the gallery) internal structural cracks.

The potential for internal cracking manifests itself through the stress distribution between the dam and the rock. As shown in Figure 15, there is along the base an intermediary zone of both high tensile stresses, and upward displacement along the central core. As a result of this, in subsequent analyses, joint elements were placed between the rock and the concrete.

Finally, the proposed model (Saouma & Perotti, 2005) was compared with the State of the Practice model. Both models were calibrated to yield the same crest displacement after fifty years, however the former assumed the sigmoid expansion curve, and the later a linear one.



Comparing the two internal maximum stresses, Figure 16 it is clear that the State of the Practice model is greatly underestimating the magnitude of the tensile stresses. This can be attributed to the lack of AAR strain redistribution in that model, as well as the lack of thermal sensitivity of the model.

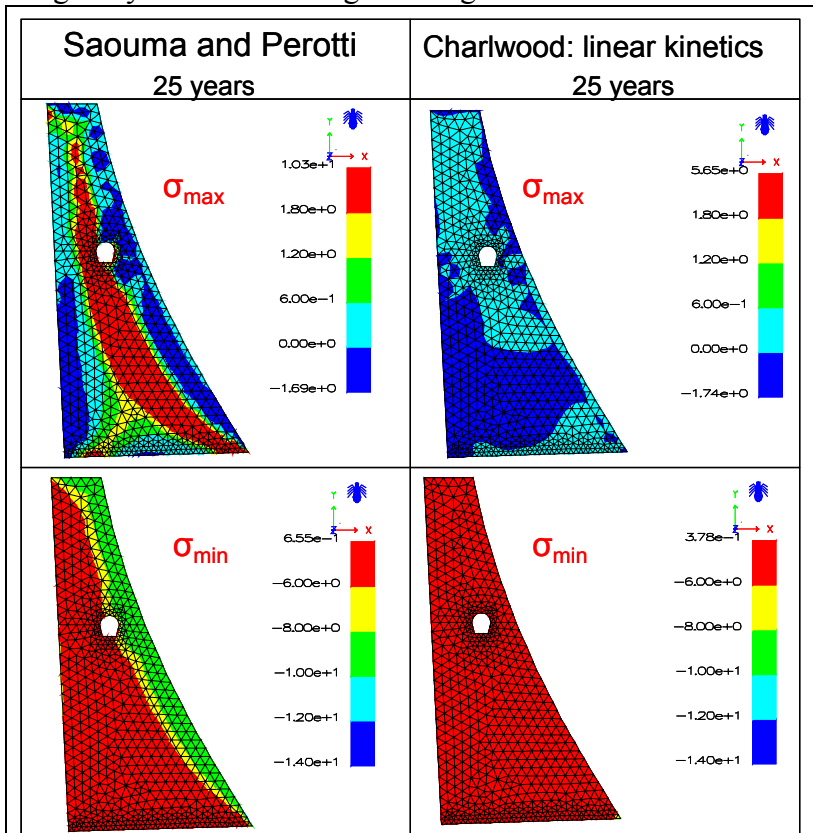


Figure 16 Proposed State of the Art Model, versus State of the Practice Model.

Finally, and with regard to the original objectives of this preliminary parametric study, it was concluded that:

1. We must model temperature temporal variation; one cannot use a constant average temperature.
2. Hydrostatic/Uplift load is important only to assess failure; effect on AAR induced response is minimal. However for dams above 50 m, they should be included in all analyses.
3. Must use 12 or 24 increments per year to correctly capture the effects of temperature variation
4. No need to model inner and external concrete separately.
5. The State of the Practice

model, when calibrated to yield same displacements as Saouma/Perotti, yields stresses which are un-conservative.

6. AAR causes a bulging in the displacement and tension in the center. This is important as it may cause internal unnoticeable cracks, and may explain the cracks observed inside the Gallery.
7. Foundation/dam interface must be modeled.

### 3D ANALYSIS

Following the 2D parametric analysis, the 3D analysis was conducted. The initial mesh is shown in Figure 17, and the 3D transient thermal analysis results are shown in Figure 18.

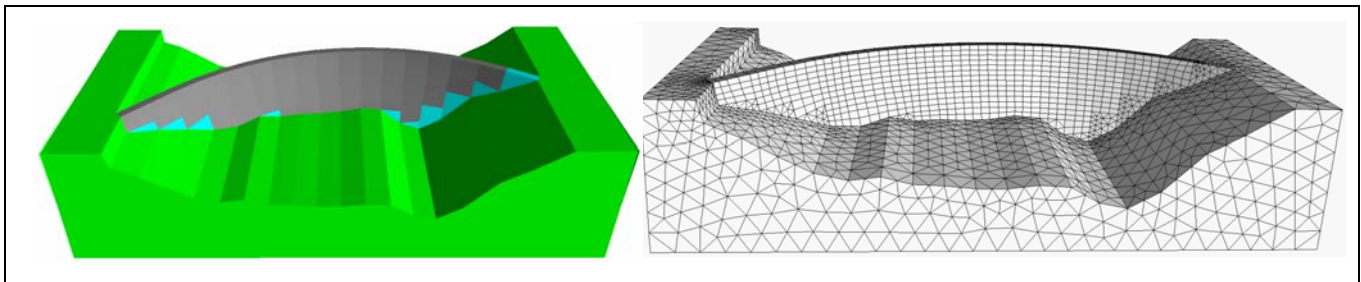


Figure 17 3D Mesh

As a result of the initial 3D parametric study, key analysis parameters were identified, and this final analysis encompassed three parts:

1. Thermal analysis of a mesh without the joints.
2. Parametric identification study of the dam up to 1997.
3. Final predictive analysis using the AAR parameters  $\tau_L(\theta_0), \tau_C(\theta_0), \epsilon_{\theta_0}^{\infty}$  identified in the previous analysis.

Despite the coarser mesh, and an ATU of 1 month, the computed internal temperature map was almost identical to the one obtained from the 2D analysis with a finer mesh.

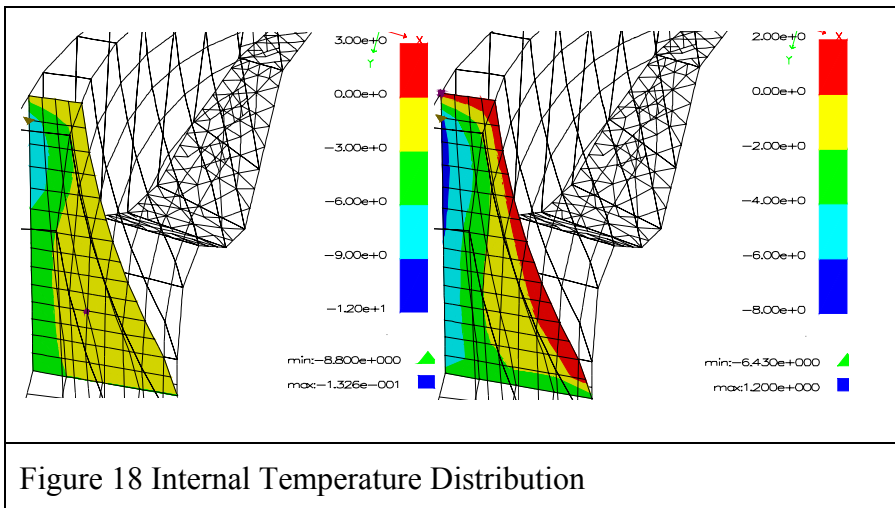


Figure 18 Internal Temperature Distribution

### Parameter Identification

Of paramount importance to the long term reliable prediction of the dam response, is the ability of the model to also simulate the past response. In a dam, we always have a record of the crest irreversible displacement with time, it is precisely this curve that a model should be able to duplicate as well as

possible. Hence, using the approach previously described, a MATLAB<sup>®</sup> “driver” program was

written to identify the three key parameters  $\tau_L(\theta_0), \tau_C(\theta_0), \varepsilon_{\theta_0}^\infty$ , by continuously comparing the histogram of crest displacement computed with the one recorded. The driver will

1. Launch an initial finite element analysis
2. Open the output file, extract the crest displacement histogram.
3. Compare the numerical histogram with the field recorded one. If results are nearly similar, stop execution.
4. Appropriately modify the input key parameters, launch the finite element analysis.

This procedure is best illustrated by Figure 19 where Left: Matlab® code; Upper Right: Finite Element Analysis Program Execution; Lower Right: Comparison of Computed and Recorded Crest Displacement (upper left), and Variation of  $\tau_L(\theta_0), \tau_C(\theta_0), \varepsilon_{\theta_0}^\infty$  vs Iterations

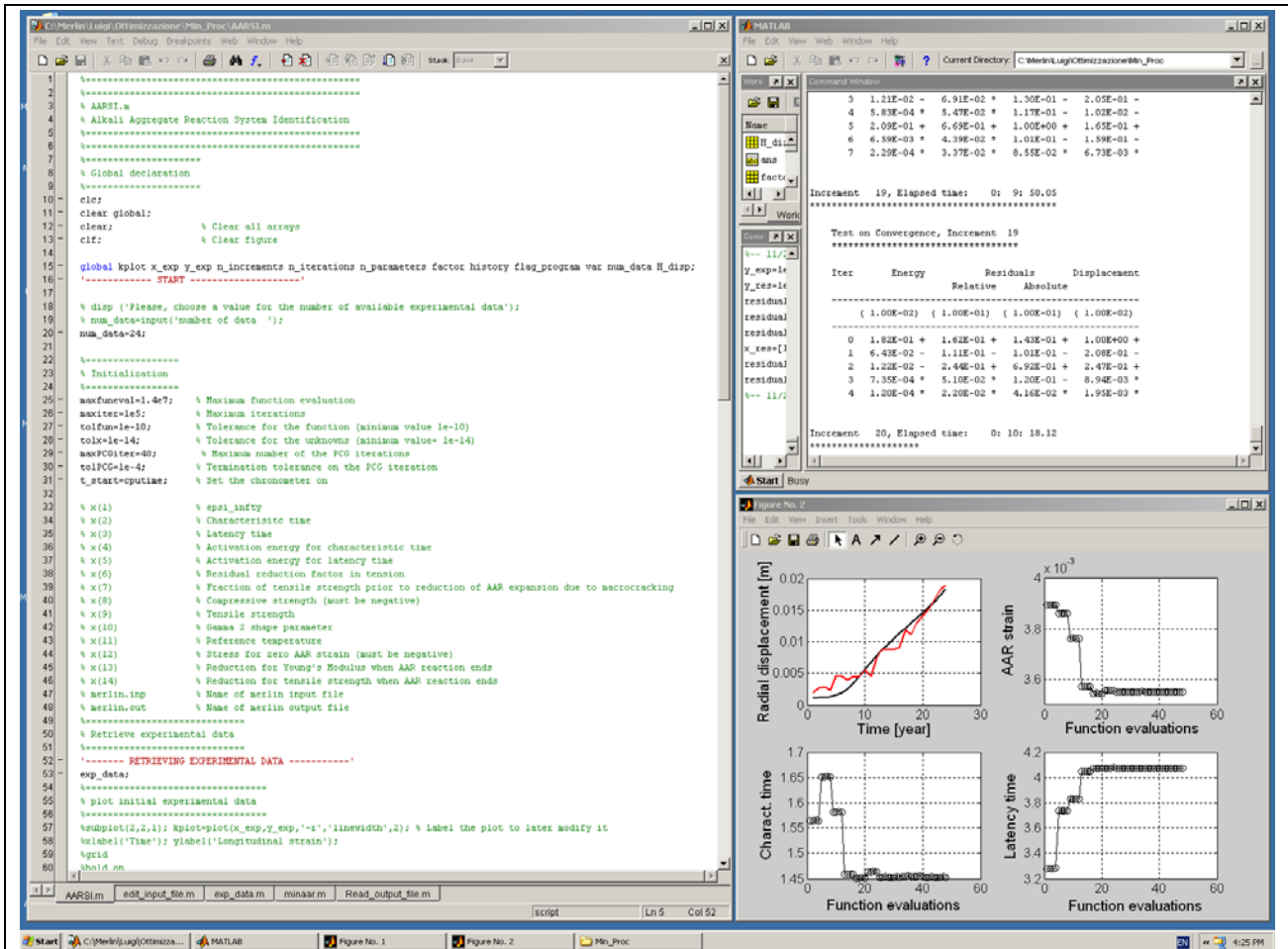


Figure 19 Graphical User Interface for AAR Parameter Identification.

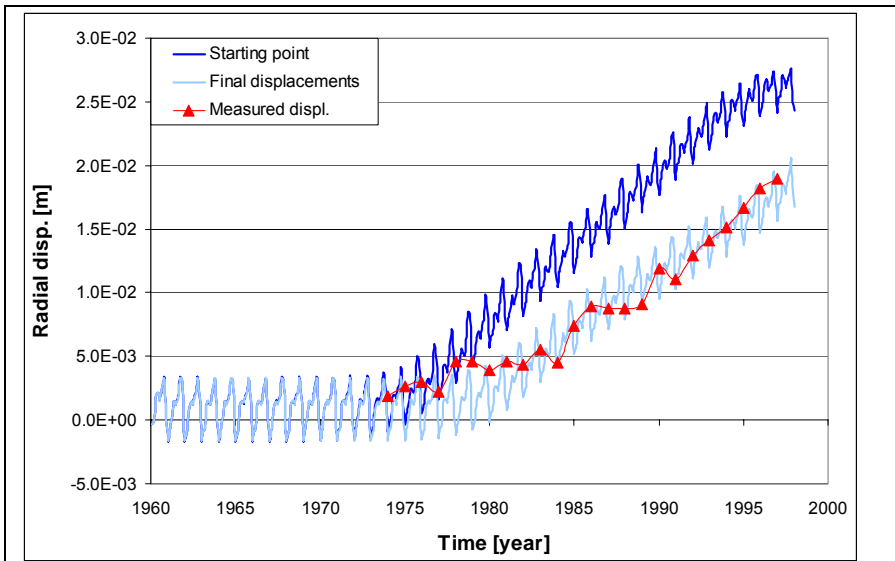


Figure 20 Comparison Between First “Guess” Analysis, and Final One with Optimized Parameters

At this point, satisfied with the ability of the program to simulate dam displacements up to 1997, a single final analysis was conducted up to 2020. It was determined that the expansion should stop around 2010.

For the 3D mesh (7,552 nodes and 5,196 elements) the total identification procedure took about 190 hours on a Pentium IV computer. Figure 20 shows the crest displacement histograms for the initial analysis (guessed parameters), final one after the parameter

identification, and the field recorded curve, and Figure 21 shows the internal maximum principal stresses.

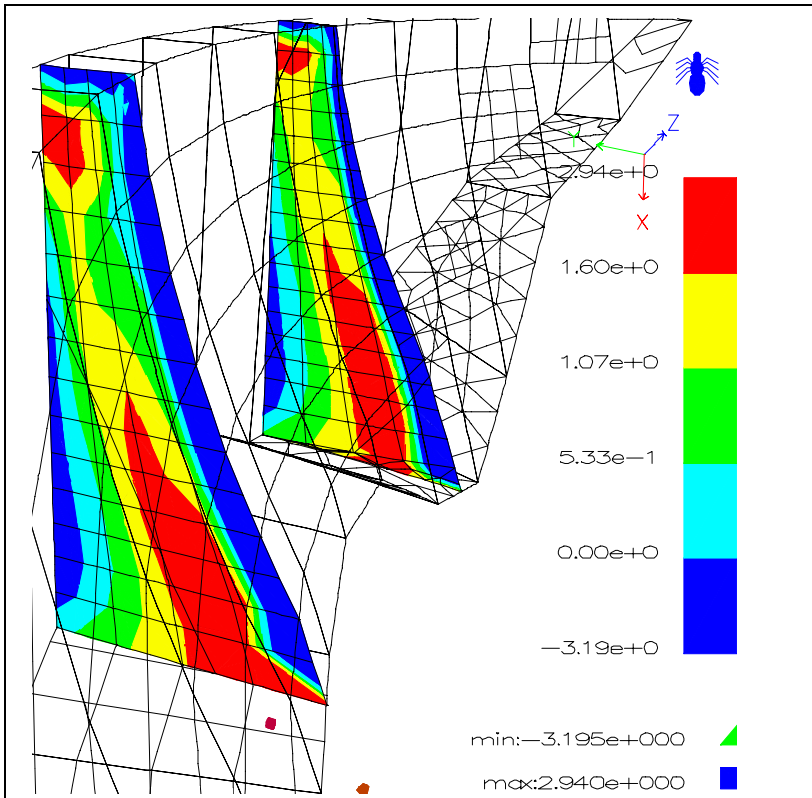


Figure 21 Internal AAR Induced Maximum Principal Stresses

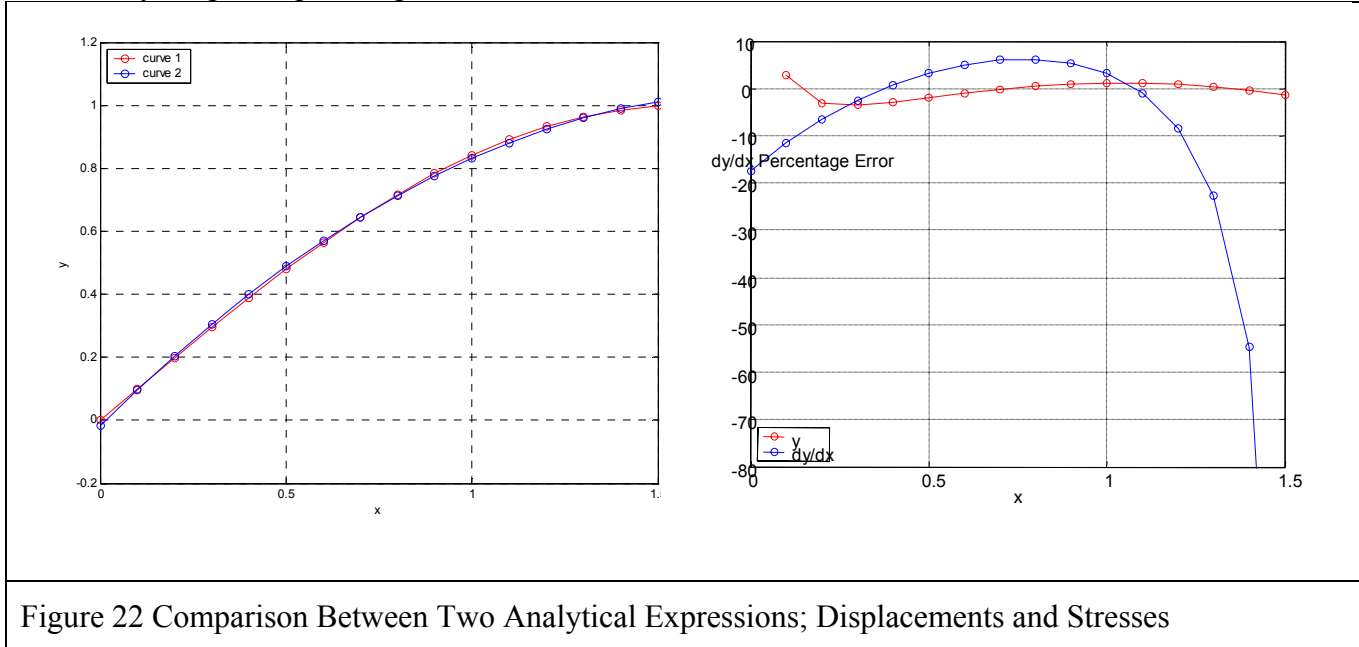
## SUMMARY AND CONCLUSIONS

Whereas most publications deal with AAR from a “material” point of view, this paper presents a constitutive model for AAR expansion, its implementation in a finite element code, and its application to a real structure.

Despite its “academic” roots, this model is not only on very scientific and solid “ground”, but it is also implemented in such a way that it can be easily used for practical engineering structural analysis. Hence, reliable long term prediction of the structural response of AAR affected structures is now possible.

Finally, a word of caution. It is not enough for a model to simply capture

the recorded crest displacements to make it reliable. What is most important is the reliability with which the stresses are computed and those are proportional (in a linear elastic case) to the first derivatives of the displacements. Indeed, as shown in Figure 22 are two analytical expressions which are nearly superimposed, yet there is a large discrepancy between their derivatives. Finally, whether this model is used or any other, it is of the utmost importance that the model be as scientifically rooted before any long term planning is undertaken.



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