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To cite this version:

Jean François Seignol, Liviu Boldea, Raphaël Leroy, Bruno Godart. Numerical model applied to the reassessment of the serviceability and safety of AAR-affected power-plant. ICAAR 2016 - 15th International Conference on Alkali-Aggregate Reaction, Jul 2016, Sao Paulo, Brazil. 10p. hal-01513392
NUMERICAL MODEL APPLIED TO THE REASSESSMENT OF THE SERVICEABILITY AND SAFETY OF AAR-AFFECTED POWER-PLANT

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Abstract

Veytaux power-plant is a hydraulic facility affected by AAR. The concrete deformations of the structure are transmitted to sensitive equipments connected to it with major consequences on the serviceability and safety. Predicting the amplitude and rate of future displacements is an essential condition to choose the manager’s strategy: adaptation of the equipment, repair or strengthening of the structure...

The main difficulty lies in the heterogeneous moisture distribution which induces complex expansion gradients and the complex interactions between chemically-induced swelling and mechanical resistance of less-affected parts of the structure.

Hence, the prediction of the displacement transmitted to the equipments requires a complete chemo-mechanical model of the structure. A macroscopic model is used and takes into account various coupling with moisture, temperature and stress states in the concrete. Its fitting requires several data: material samples from the structure for laboratory tests, monitoring devices for measuring displacements, moisture and temperature..... The resulting heterogeneous displacements in the concrete structure allow to re-assess the stress-state generated in the anchored equipment, especially in the 130-m long main distributor pipe.

Keywords: FEM, hydroelectricity, structure, prediction, serviceability

1 INTRODUCTION

In the case of a hydraulic powerplant, alkali-aggregate reaction (AAR) results in concrete swelling which induces strains directly transmitted to sensitive equipment connected to the structure: generators, turbines, pumps and distributor pipes are then affected by differential displacements and potential stresses which may strongly modify their serviceability and safety. From the manager point of view, predicting these displacements and their consequences onto equipments is a key point in choosing a strategy for affected facility.

The Veytaux powerplant is composed of four pump-turbine units mounted on the same number of blocks originally separated by construction joints. AAR affecting the four books results in continuous deformation of the slabs and their supports composing each block, and hence heterogeneous displacements transmitted to the anchor of the main equipments. They require periodical readjustment, which raises questions about future serviceability of the facility. The prediction of these displacements requires the complete chemo-mechanical modelling of the structure, taking into account heterogeneous expansion mainly due to complex moisture distribution. A finite-element model is proposed, as well as its fitting based on various data from monitoring of the powerplant. The resulting heterogeneous, time-varying displacements obtained for the upper slabs are then used to re-assess the stress-state generated in the anchored equipment, especially in the 130-m-long manifold distributing water to the four hydro-electric groups.

The first part of the paper describes the AAR-affected powerplant and the general organization of the study. The second part deals with the numerical modelling of the concrete structure. The third one focuses on the numerical models used to represent the manifold, their boundary conditions given by the previous simulation and the assessment of the AAR-induced stress-state. Lastly, the paper concludes with maintenance strategy chosen by the structure-owner based on this numerical study.

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OVERVIEW OF THE STUDY

2.1 Veytaux Powerplant

The Veytaux facility, in Western Switzerland, is operated by Forces Motrices Hongrin-Léman (FMHL), a company of Alpiq founded in 1963. The underground power plant, built in 1968, produces electricity with its four 60 MW-generators by turbining water at 32 m$^3$/s from the Hongrin reservoir (52 million m$^3$) some 800 m above. During hours of low consumption or excess of renewable electricity production, water from Lake Geneva is pumped back into the Hongrin reservoir at 24 m$^3$/s.

The plant consists of four quite similar blocks, side by side in a rockcavern. Each block is about 30 m by 30 m and its three stories total a height of about 10 m. Each block is composed of an upper slab (level 0) on which the hydro-power equipment (pumps, turbines, alternators, pipes...) is anchored (Figure 1). The upper slab is supported by various walls delimiting technical spaces in levels -1 and -2. Along one of the sides is the tailrace tunnel, allowing water to reach Lake Geneva. This channel represents the main source of moisture in the concrete structure.

2.2 Consequences of AAR in the structure

Since the commissioning of Veytaux power plant in 1972, movements in the slab at the level 0 were observed. Laboratory tests conducted on cores taken from the concrete of the structure have confirmed the presence of AAR. The concrete has been affected to various degrees by the pathology, especially in the elements which are highly exposed to humidity (walls in direct contact with water or damp rock). This results in anisotropic strain that contributes to amplifying the mechanical problems when reassembling the elements after revision; it concerns the valves, turbines and pumps. These recurrent problems tend to amplify with each revision.

The reaction also affects the 4 slabs at level 0 which support the equipment, leading to the joints closing between the 4 corresponding blocks. The leveling measurement records of the equipment foundations, begun in 1984, suggest that the slabs have been lifting at a rate of 0.1-0.2 mm/year for at least 20 years. Distributed over an average height of 10 m for the total 3 levels of the plant, this corresponds to a lift rate of 0.002%/year. It appears therefore that the AAR in the slabs is less severe than in the concrete elements directly in contact with water or damp rock. This deformation, however, creates important mechanical problems which are unacceptable for the pumps and turbines.

Since the joints between the 4 blocks of the plant closed a few years ago, most of the horizontal deformation of the concrete slab takes place at the apertures of the pump and turbine shafts, leading to increasingly serious mechanical problems.

2.3 Strategy for managing the affected structure

General

For the moment, problems appearing when the valves are reassembled have been solved by grinding the attachment bolt holes in the supporting concrete and the use of skewed rings. At each reassembly, the sphere valves between the collector-distributor and the units, both for the turbines as well as the pumps, raise problems of misalignment with the foundation. At present, all the turbine valves have had their attachment bolt holes ground, but it is not sufficient and needs to be redone at each disassembly. These misalignments logically lead to problems of parallelism which cannot be compensated by grinding the bolt holes. The clamps are forced, causing strain in the collector-distributor manifold.

Hence, a methodology to predict displacements has been decided, based on numerical models the fitting of which is allowed by exploiting the monitoring of the powerplant.

Monitoring and sampling

A comprehensive monitoring system was set up in the powerplant, including Invar wires deflectometers, temperature and moisture gauges. It completes the existing monitoring system, especially the periodic leveling of the upper slab for which data exist for more than 30 years. This system has been described in [1].

In addition, several sample cores were drilled out of the structure to assess concrete characteristics such as Young modulus, Poisson coefficient, AAR reactivity, etc. Most of the monitoring and sampling was realized in block 1: our strategy was to fit the constitutive model only for this block with as many data as possible and then apply the same model to the other blocks, considering they are made of the same material.
Numerical modeling

Numerical modeling of Veytaux powerhouse was therefore realized in three steps:

- numerical modeling of block 1 based on finite-element description and fitting of its parameters based on monitoring and samples;
- applying the same parameters to finite-element modeling of blocks 2 and 3 (only one mesh, since both blocks are similar) and finite-element modeling of block 4;
- applying the displacements obtained from steps 1 and 2 to the anchoring points of the finite-element modeling representing the manifold to assess its stress-state.

3 NUMERICAL MODEL FOR CONCRETE STRUCTURE

The powerhouse is modelled with the FEM-software CESAR-LCPC using the RGIB module devoted to AAR-affected concrete structures. The principles of this simulation is presented in [1] and [2] and is briefly summarized infra.

3.1 Numerical procedure for re-assessing AAR-affected structures

The RGIB-module of CESAR-LCPC software is based on a concrete constitutive equation taking into account AAR-effect as a time-dependant prescribed expansion. This expansion, based on Larive’s S-shape curve, depends on material moisture and temperature [3].

\[
\varepsilon_x(0) = \varepsilon_\infty \cdot \xi(t) \cdot A_i \\
\xi(t) = \frac{1 - \exp(t/\tau_c)}{1 + \exp\left(-\frac{t - \tau_l}{\tau_c}\right)} \\
\varepsilon_x(\sigma) = A_e(\sigma) \cdot \varepsilon_x(\sigma)
\]

In these expressions were bold letters represent tensor, stress-free induced strain is the product of total swelling potential \( \varepsilon_\infty \) times chemical extent \( \xi \), which is a dimensionless function of time \( t \) and times a diagonal tensor \( A \) representing a possible swelling anisotropy (or identity tensor if concrete free-swelling is supposed isotropic). Chemical extent is governed by Larive’s law implying two parameters: characteristic time \( \tau_c \) and latency time \( \tau_l \). The influence of stress-state \( \sigma \) is described by tensor \( A_e \), which binds real swelling to free swelling. Its properties are described in [4]. Modification of concrete mechanical properties caused by micro cracking due to AAR gel is also considered with the damage model described in [5].

The model parameters are then modified by thermal and moisture conditions at each location in the structure, according to coupling equations presented in [1]. Three FEM-computations are then performed on the same mesh. The first one consists in solving the heat transfer equation in the structure and the second one is based on a water-diffusion problem. Last, the AAR-induced chemical expansion is computed for each time-step and each finite-element and introduced into the mechanical problem as a prescribed strain.

3.2 Finite-element model for the concrete structure

Three finite-element models have been realized, representing respectively block 1, identical blocks 2 and 3, and block 4 (the last one can be seen on Figure 2). Each block is represented by about 20,000 sold elements which allow to assess transversal moisture gradients in the walls. Bar elements are also used for prestressed cables reinforcing some parts of the powerhouse (whereas rebars are taken into account by increasing concrete stiffness through an homogenization procedure).

3.3 Fitting of AAR-model

Fitting of the constitutive equations is performed by modeling block 1 behaviour since initial time \( h_0 \) corresponding to end of construction (year 1968) until present time, with constant time-step equal to one year. Moisture and temperature fields are assessed with boundary conditions given by mean relative humidity and temperature monitored in the powerhouse.

According to method described in [6], the fitting consists in modifying Larive’s law parameters until computed vertical displacements are close enough to measured the ones obtained by leveling of the upper slab, which leads to:

- \( \varepsilon_\infty = 1200 \mu m/m; \)
- \( \tau_c = 150 \text{ days} \);
- \( \tau_l = 700 \text{ days} \).
Note that these parameters are given for a relative humidity of 100% and (as regards with characteristic and la teney times) a temperature of 38 °C.

3.4 Consequences of AAR

Concrete swelling in the powerhouse is heterogeneous mainly due to non-uniform relative humidity field (elements in contact with the tailrace tunnel, pumps or turbines are saturated whereas the ones close to electric devices such as transformers receive heat which helps drying), as shown on Figure 3. The induced variation in swelling amplitude and rate, coupled with diverse thicknesses and stiffnesses of walls supporting the upper slab leads to contrasted displacements in the slab as presented on Figure 4. These displacements are likely to increase in the future: Figure 5 shows predicted deformation 100 years after construction, in 2068.

The concrete structure deformation may raise difficulties in itself, essentially because it creates distortions in some structural elements which could damage them. Such a distortion is represented on Figure 6 for the support of a booster pump. It is induced by contrasted moisture states on both sides of the pit, and the model behaviour was confirmed by visual inspection of this support which revealed a fracture.

But the main concern in serviceability is about equipments anchored in the slab. The various fixation points are submitted to different displacements and these gradients are responsible for disturbances and efforts in the powerhouse machinery. Figure 7 presents relative horizontal displacements in the direction perpendicular to the shaft (point 1 corresponds to the turbines, point 2 to the generator and points 3 and 4 are located on each side of the main pump). Deviations larger than 1 mm can be seen between the turbine and the generator, which must be undergone by the 10-m long shaft. Precise knowledge and prediction of these deviations are of first importance for technicians in charge of machines maintenance.

4 NUMERICAL MODEL FOR THE DISTRIBUTOR PIPES-NETWORK

Differential displacements are also transmitted to the manifold, which raises concern for the structure manager. The manifold carries water under high pressure (Hongrin reservoir is located about 800 m above the powerhouse), hence it is crucial to check the potential stresses generated by these displacements in the pipes for the sake of workers security. A complementary study was then carried out to assess the manifold stress-state taking into account AAR-induced swelling. Manifold elements considered in this study are the 130-m-long distributor, the junction pipes feeding the turbines and the connections to the main pump. The manifold is made with different kind of steel, mainly BH 47S (with tensile strength $R_m=588$ MPa) and Aldur 58 ($R_m=568$ MPa), and is represented by an elastoplastic constitutive equation associated to von Mises yield criterion.

The mechanical modeling considers manifold dead-weight, inner 100-bar-water-pressure, thermal effects, displacements from 1968 to present day and predicted displacements until the end of the simulation period, in 2068. Maintenance operations including disconnecting and reconnecting some parts of the manifold were also taken into account.

4.1 Interaction between concrete structure and pipes network

The modeling consists in applying the displacements computed by the FE-models of the four concrete blocks as boundary conditions to the FE-model of the manifold. But one should also consider the effect of the manifold stiffness onto the concrete structure deformation, since it is well known that applying a mechanical restraint to AAR-affected concrete may lower the chemical expansions. To assess this effect, a simplified model is realized by adding beam elements onto the FE-model representing block 1. Each beam is affected with mechanical properties representing manifold elements stiffness. This model is presented in Figure 8: distributor is in red, junctions to the turbines are in purple and orange and junction to the main pump in yellow, whereas the positions with letters correspond to the manifold supports.

By comparing displacements obtained on the upper slab to the one computed without manifold, relative difference lower than 6% is obtained. Hence, stiffness of the manifold can be neglected in the assessment of displacement on the slab, and this validates the principle of the next model.

4.2 Finite-element models for pipes-network

The study was first realized with a global model representing the whole manifold and its supports but it turned out to be too complex and too large to be correctly used (see Figure 9). This is why a simplified global model was designed for each block with overlapping at the borders. Each of
these models is made of 3D shell-elements with beams representing supports or connections (see Figure 10). Refined models are also used for local studies, such as the one represented on Figure 11. These models consist mainly in 3D solid elements; some stiffener or support, made of thin plates, are represented by shell elements. The modelling was conducted with SCIA Engineer software.

4.3 Numerical results and consequences

Two series of modelling were performed onto these models (as well as sensitivity analysis): assessment without AAR, considered as a reference stress-state, and introduction of AAR-induced displacements of the support, to assess real stress-state, at present time first, then with predicted evolution of the pathology.

Reference assessment considering a normal situation (without AAR) result in important stress level but in accordance with safety criteria for such equipment. As an example, Figure 12 represents the stress field in the junction with the pump at present and future time. The water-pressure was increased by about 20% to take into account transitory phases.

Taking into account AAR-induced displacements in supports increases stress level in critical zones. The main concerns are for the branching connecting distributor pipe to the pump-vanes, especially near the distributor strengthening (see Figure 13).

Based on these results, adjustment operations have been carried out during a long-duration shut down for maintenance: stress liberation has been realized onto the 8 turbine-vanes and the 4 pump-vanes in order to turn back to an “ante-AAR” stress-state. Stress-free connectors, skewed rings and a monitoring system with laser trackers have also been installed.

5 CONCLUSIONS

This study of a real case of AAR-affected powerhouse focuses on the use of numerical modeling to design a maintenance policy taking into account serviceability decrease in the facility and ensure security in equipments connected to the concrete structure. The main conclusion drawn from both field observation and numerical modelling is that, in the case of this kind of hydropower facilities, AAR consequences have to be considered in the concrete structure itself, but also (and essentially) in the equipment and machinery connected to the structure.

The three steps of the modeling have been described: fitting the constitutive equations of the AAR-affected concrete with the results from monitoring and sample cores of one quarter of the power-house; modeling and predicting the deformation of the whole concrete structure; applying the obtained displacement to a model representing the manifold and assessing both its present and its future stress-state.

This procedure allows to provide the structure manager with useful information about the stress-state induced in the manifold by the irreversible displacements of its supports connected to the concrete structure and to define a maintenance strategy for the machinery.

The authors would like to express their warmest thanks to Patricia Roure (Itech software) for her important and appreciated help in the numerical modelling.

6 REFERENCES

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FIGURE 1: General view of the slab and its four blocs (left); distributor pipe and its manifold (right).

FIGURE 2: FE mesh for block 4 (left) and internal details without upper slab (right).

FIGURE 3: Relative humidity in cross-section of block 1 near the pump. Blue zones are saturated (such as outlet channel on the right), green ones are under 80% RH.
FIGURE 4: deformation in block 1 and color map for vertical displacement (from 0, blue, to 16.5 mm, red) at present time.

FIGURE 5: deformation in block 1 and color map for vertical displacement (from 0, blue, to 16.5 mm, red) in 2068.
FIGURE 6: deformation in block 1 and color map for global displacement (from 0, blue, to 16.5 mm, red) at present time in a cross-section through the pump pit.

FIGURE 7: relative transverse displacements of 3 couples of points at the supports of the machinery versus time (in years): turbine/generator (blue), turbine/pump (red and green).
FIGURE 8: Simplified model of block 1 with beam elements representing manifold stiffness.

FIGURE 9: Global model representing the whole manifold and its supports.

FIGURE 10: Simplified model for the manifold on one block and injection of prescribed displacements into the supports.
FIGURE 11: local model for the supports and connections of the pipes between the distributor and the turbines.

FIGURE 12: von Mises stresses in the junction with the pump, reference state.

FIGURE 13: von Mises stress in the connection between distributor and pump-vanes, AAR taken into account.