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DIAGNOSIS OF THE CAUSE OF THE PROGRESSIVE CONCRETE SWELLING AT THE PAULO AFONSO I, II, AND III UNDERGROUND POWER STATIONS

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ABSTRACT

The underground Power Stations of Paulo Afonso I, II and III are located in the São Francisco River, in the northeastern part of Brazil. These Hydroelectric Power Stations were commissioned between 1954 and 1971, with a total hydraulic head of 82 meters and turbines from 60 to 216 MW. The concrete structures employed granite-gneiss as aggregate, with strained quartz as reactive mineral.

The first signs of concrete deformations were observed in PA-I and PA-II at the end of the seventies, in the form of cracks, opening of joints between concrete layers and compression rupture of some concrete pillars on the lateral side of the PA-II underground power station. Some of the multiple extensometers installed in the early nineties are showing concrete expansion rates between 40 and 50 micro strains per year, which of course is influenced by the confining stresses.

This paper presents some of the results of the detailed investigations related to the diagnosis process, including the laboratory tests, the monitoring instruments installed for measuring the concrete expansion along the vertical, longitudinal and transversal directions, the measurement of the natural concrete stresses, etc. Special emphasis is given to the modeling of the underground concrete structures, where the concrete expansion is causing electromechanical problems. The first results of the mathematical model of the PA-II and PA-III Power Stations are presented.

Keywords: Alkali-aggregate reaction, mathematical model, monitoring, concrete laboratory tests, remedial measures.

INTRODUCTION

The history of the Paulo Afonso Power Plants began with the establishment of CHESF (Companhia Hidro Elétrica do São Francisco) in March 1948, responsible for the construction, thus exploiting the hydraulic potential of Paulo Afonso Falls, in the São Francisco River.

The construction of Paulo Afonso I began in March 1949, and was entirely performed by CHESF. The main characteristics of the plant are the following: constant storage volume, concrete gravity dam with a total length of 4215 m, outflow system with a capacity of 22,000 m^3/s and underground power station with three units of 60 MW each, having its commencement of power supply in 1954. The construction of Paulo Afonso II began in 1955. Three units of 75 MW are operating since 1961 and another three units of 85 MW each, are operating since 1967. Paulo Afonso III had its design refined in relation to the previous power plants. This was due to the position of the water intake, which was designed next to the river canyon, achieving a better gross head efficiency. Construction started in 1967 and is in operation since 1971.

Power House	PA I	PA II		PA III
Dimensions (H/W/L) (m)	31/15/60	37/18/104		46.5/18.5/127
Quantity of Machines	3	3	3	4
Hydraulic Gross Head (m)	81	82	81.5	82.5
Diameter of Penstock (m)	4,8	5,2	5,2	8
Nominal Flow Rate (m^3/s)	90	110	125	266
Rotation (rpm)	200	200	200	138,5
Turbine Power (MW)	60	75	85	216
Start of Operation	1954	1961	1967	1971

SYMPTOMS OF THE ALKALI-AGGREGATE REACTION

The first AAR symptoms were observed at the end of the seventies in PA II, that is, when the plant had been in operation for 17 years. Several sub-vertical cracks were observed in the concrete, in the walls of the generator hall, and sub-horizontal cracks along the joints between concrete layers, where the crack mapping and meters installed showed a certain evolution trend over time.

In the early eighties, some small pillars supporting cable trays in the PA-II power house, located at the side of the cave, failed by compression, because they were located between the mass concrete structure at turbine level (under expansion) and the floor support beam at generator level.

Samples of concrete from PA-I and PA-II power plants were tested by ABCP (Brazilian Association of Portland Cement), through analysis of petrographic slides and electronic microscope. The samples tested were cylindrical specimens with 11 cm diameter and 1 m length, extracted through rotating boreholes.

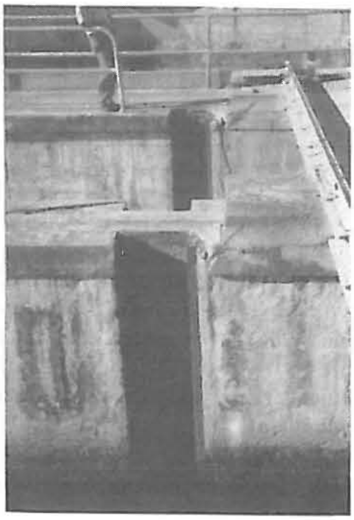
Regarding AAR symptoms, the results of these tests showed the following:

- Signs of dark rims around the aggregate particles;
- Some voids filled with whitish material;

- Absence of cracks at the aggregate particles and around;
- Aggregate debounded with AAR typical materials observed at the paste/aggregate interface.

Therefore, the conclusion was that the tests performed provided evidence of alkali-aggregate reaction due to the presence of strained quartz. The reaction observed is of the alkali-silicate type, normally characterized as slow, although in the Moxotó Power Plant , probably due to high ambient temperatures of the region, this reaction occurred relatively fast and with expansion rates up to 80 με/year (Cavalcanti et al. 1992). The aggregates of gneiss rock and some type of granite ,with more fine particles apparently more strained or mylonitized, seems to be potentially more reactive

Evidences of AAR were also observed in other parts of the concrete structures, like the intake of PA-I, where the concrete swelling along 45 years caused the rupture of the concrete near the stop-log steel guide, as indicated in Photos 1 and 2.



Photos 1 and 2: Abnormal changes in structural dimensions at the stop-log steel guides.

IN SITU AND LABORATORY INVESTIGATIONS

It was decided to perform a detailed research of the concrete physical and mechanical properties of the three underground power plants, together with accelerated reactivity tests in mortar bars and concrete samples, as well as the determination of the concrete damage rating, according to the procedures suggested by Grattan-Belew (Grattan-Belew et al. 1992).

For concrete sampling, boreholes were drilled for the installation of horizontal and vertical multiple extensometers, supplemented with 8" diameter boring holes, specially executed for extraction of concrete sampling, to perform concrete tests of compressive strength, diametrical tensile strength, Young's modulus, Poisson's ratio, creep parameters and damage rating. The 3" ϕ (7,6 cm) samples were used for executing petrographic tests, determination of concrete unit weight, determination of total and soluble alkali content, determination of concrete expansion and accelerated potential reaction tests. The expansion tests with 3"ϕ (7,6 cm) specimens are being carried out with samples exposed to 100 % relative humidity air at 38° C, and in a 1N NaOH solution, also at 38° C.

The places for removing the concrete samples were always selected from mass concrete structures, avoiding slim structures, since in these the existing instrumentation did not detect the occurrence of concrete swelling. Sample points located at different structure blocks and at different elevations were then selected. The samples were protected against moisture loss, by wrapping them with tensoactive plastic sheets, immediately after taking them from the structures. Table 1 shows the total length of samples to be removed from each power plant.

TABLE 1 : List of Boreholes to be Performed on each Power Plant

Type of boring	Borehole diameter	Length (m)			Total (m)
		PA-I	PA-II	PA-III	
For concrete sampling	ϕ 8"	15.0	21.0	16.5	52.5
For monitoring instruments	ϕ 3"	45.0	105.0	141.0	291.0
Total		60.0	126.0	157.5	343.5

MONITORING SYSTEMS

The first monitoring instruments installed in the Paulo Afonso power plants date from the 70s, when some electric meters were installed for joint measurement, supplemented by glass slides glued over cracks and joints of larger opening. In 1989 some multiple rod extensometers were installed in the concrete structures of PA-II and PA-III (installed in 1995), which strains, up to the present date, are registering the expansion rates indicated in the following table:

TABLE 2 : Annual Concrete Expansion Rates in PA-II and PA-III Powerhouses

Multiple extensometer	Expansion rate 1989 – 1999 ($\mu\varepsilon$/year)	
	PA-II Powerhouse	PA-III Powerhouse
SubVertical	45 (GR2) - 35 (GR5)	--
Horizontal	50 (GR2)	40 (1996 - 1997)

The concrete expansion rates of PA-II power plant were observed by a larger number of instruments, being therefore more representative. The smaller concrete expansion rate in the vertical direction, was attributed to the restrictions imposed by the rock mass, since the vertical extensometers are only approximately 1.5 m away from the rock wall.

As a consequence of the small quantity of instruments installed, recently, a project for supplementing the monitoring instrumentation was prepared, with the purpose of measuring the concrete expansion rates in the vertical, longitudinal and horizontal directions, through rod multiple extensometers, superficial bench marks and joint meters. These instruments were also supplemented with some thermometers and weir gauges, as listed in Table 3.

TABLE 3 : List of Instruments to be Installed

Type of Instrument	Hydroelectric Powerhouse		
	PA-I	PA-II	PA-III
Multiple rod extensometer	3	8	7
Triorthogonal joint meter	4	9	3
Thermometer embedded in concrete	2	2	2
Surface thermometer (air)	3	3	3
Leveling bench mark	5	10	7
Weir gauge	2	2	2
Total	19	34	24

The bench marks will be installed on the generator's floor, with the main purpose of following up the upward vertical displacements resulting from concrete expansion, affecting the behavior of the electromechanical generation equipment.

TRIDIMENSIONAL MATHEMATICAL MODEL

Since the main objectives were the investigation of the diagnosis picture and especially the efficiency of the remedial measures, finite elements mathematical models were prepared for the PA I, II and III underground powerhouses, processed with the ANSYS software, version 5.5, comprising basically all the units and the surrounding rock mass, were the bordering conditions were applied. These models can be considered as large-size ones, resulting in a discretization of about 50,000 DOF (degrees of freedom), 10,000 nodes and 40,000 solid, linear and plane elements. In Fig. 1 it is shown the finite element mesh of the concrete structures of PA-II powerhouse.

The laws that rule the expansion phenomena as well as the visco-elastic properties of the concrete were applied using software (MACRO), in FORTRAN language, that controls the commands offered by the ANSYS software.

During the last decade various procedures for simulating concrete swelling were proposed. Laboratory researches on swelling reaction show that the confining stresses in the structure influences the AAR, reducing the swelling rate up to a zero limit. In structures embedded in underground cavern, such as in the case of PA I, II and III powerhouses, compressive stresses tend to increase with time, conditioning the concrete swelling rate (Adegue et al. 1995).

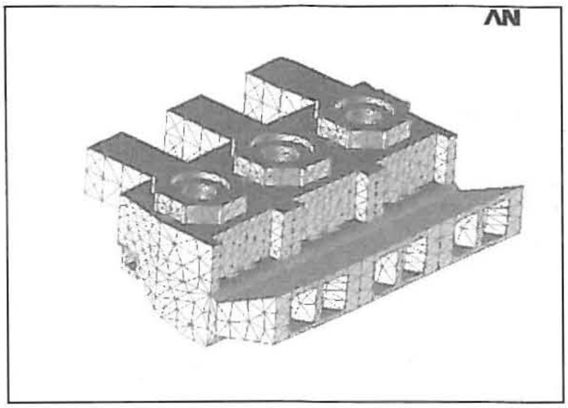


Fig. 1 : Finite element mesh for PA-II Power Plant – Concrete structures

In order to simulate the expansion of concrete with a rate depending on the stress condition, the initial analysis were made in stages simulating one year of expansion. For this analysis overlapping of the various effects was deemed acceptable. The analysis were carried out in an iterative manner, within the elastic regime, stage by stage, obtaining the concrete expansion rate as a function of the accumulated stresses up to the previous stage, in every concrete element and considering the three Cartesian directions. In Fig. 2 is graphically illustrate the proposed simulation, as well as the parameters adopted in this phase of the study (Thompson et al. 1994).

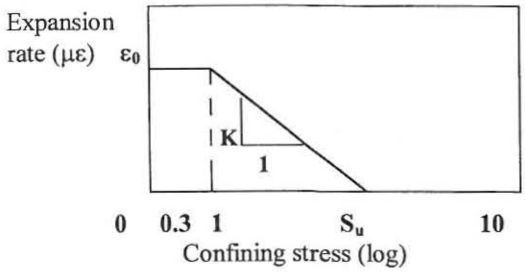


Fig. 2 – Expansion rate x Confining stress S (MPa)

$\varepsilon = \varepsilon_o - K \,.\, \log (S/S_0)$

Where: ε = expansion rate (ε_x, ε_y, ε_z)

S = confined stress (S_x, S_y, S_z)

ε_o = expansion rate without confinement (ε_0 = 50 and 80 $\mu\varepsilon$)

S_0 = stress below which the expansion is constant (S_0 = 0.3 MPa)

S_u = stress above which the expansion is zero (S_u = 4 MPa)

K = a constant defined by the slope of the straight line correlating the expansion and the log of confined stress (K = 44.5 $\mu\varepsilon$/MPa)

The initial expansion rate (ε_0) were determined from the monitoring of Moxotó and PA-IV Powerplants, while S_0 and S_u were determined from laboratory tests and other AAR papers.

Despite this formulation being valid only for compressive stress, from the engineering point of view it is possible to apply it for powerhouses affected by concrete expansions, since most of the structure is subject to compressive stresses. It was considered that during the first five years the concrete expansion rate presents linear increasing values, up to the value adopted for each power plant, being ruled from the sixth year onward by the confining stress law.

The elastic parameters of the rock mass were adopted based on the results obtained from the monitoring instruments of the de PA-IV powerhouse, located in the same region of PA I, II and III. The rock mass around the underground cavern, affected during the excavation works, was simulated with a reduced Young modulus in the first stage, being gradually increased, considering the rock mass stiffness, as a function of the concrete expansion.

The visco-elastic behavior of the concrete was simulated from the creep curves, and from these, the relaxation curves. The Boltzmann's visco-elastic model was adopted because it shows elastic and viscous strains. This model was selected because it simulates very well the features of concrete and steel, as well as the strains changing along the time. In the present study the equation below, adopted by the Bureau of Reclamation as creep function, was used.

$f(k,t-k)=1/E(k) + F(k)\ln(1+t-k)$ [1]

Calibration factors used were, basically, the expansion rate without confinement, the limit confining stress and the visco-elastic parameters of concrete. The analyses were performed on the two models of the respective power plants and the results were compared with each other, taking into account the size and the power of each one. In the mathematical model the concrete swelling was simulated through "n" stages, where "n" corresponds to a one-year period, and n=38 years was adopted, which corresponds to operational period of PA-II (1961-1999) and n=28 years, for the PA-III power plant (1971-1999). The table below presents the parameters used in these mathematical models, where models "1" and "2" tried to investigate the influence of the initial concrete expansion rate, in the displacements and deformations of the concrete structures.

TABLE 4 : Parameters Used in the PA-II and PA-III Mathematical Modeling.

Model	Initial expansion rate (ε_0)	Compressive restraining stress (MPa)	Rock Mass Modulus Er (GPa)
PAII-1/PAIII-1	50	4	15
PAII-2/PAIII-2	80	4	15

Fig. 3 presents a comparison of the strains measured by rods n° 1 and 2 of multiple vertical extensometers EM-2 and EM-5, installed in the Units GR2 and GR5 of PA-II, where it is possible to see that both models showed similar values. In general, model "1" presented a good correlation with the values measured by the instruments installed in unit GR2.

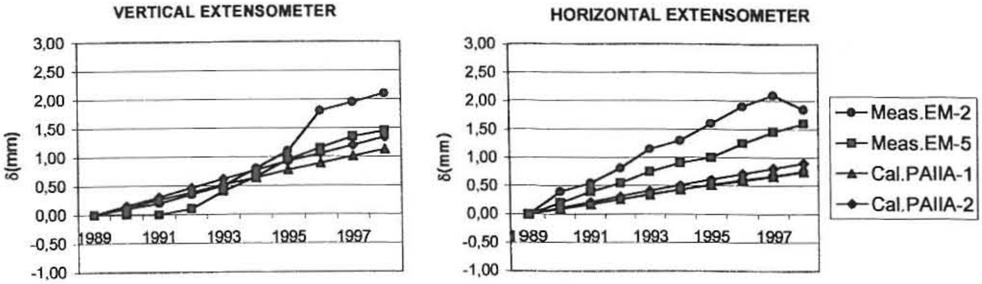


Fig. 3: Displacements calculated and measured by extensometers in PA II

As regards electromechanical equipment, the measurements of the vertical gap between wicket gates, at the inflow and outflow side edges, through which it is possible to evaluate the tilting of the vanes and compare it with the values supplied by the mathematical model. In Fig. 4 this comparison is presented for GR1 generating unit of PA-II Powerhouse, where it is possible to observe a good correlation between the theoretical and the horizontal measured displacements, between 1988 and 1993.

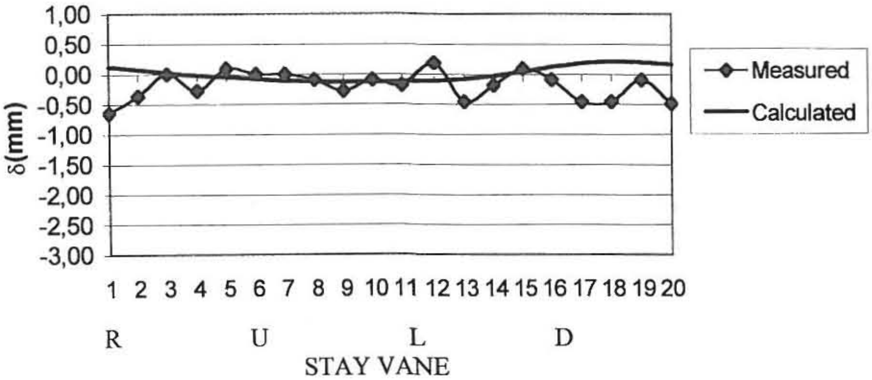


Fig. 4 : Horizontal relative displacements at the stay vanes of PA II

Although there are no stress measurement available on the stay vane, it was decided to analyze the theoretical stresses in these vane, in order to evaluate the intensity of the tensile stresses induced by the AAR. Fig. 5 presents the stress distribution on the PA-II's GR2 stay vane, for ages of 1, 10, 20, 30 and 39 years (1961-2000), where it can be observed that the maximum stresses occur downstream, with maximum tensile stresses of 161 MPa, after 39 years of AAR. The stress distribution is different for the three generating units, as a consequence of the differences in the bordering conditions and the vertical shaft downstream Unit 2, only.

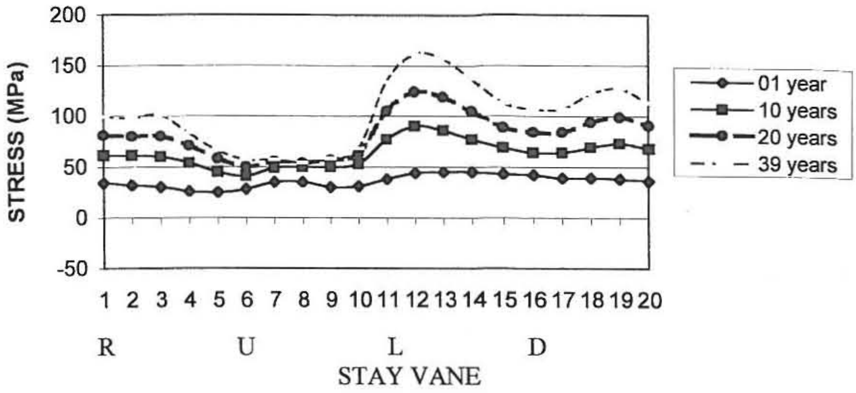


Fig.5 : Calculated vertical stresses at the stay vanes of PA II

For PA-III Powerplant Fig. 6 presents the vertical stress distribution on GR-1 stay vane, after 1, 10, 20 and 30 years (1970-2000) of AAR. As observed in PA-II, the maximum stress occurred downstream-left, with 81 MPa in stay vane N°15, while upstream the compressive stress hit - 41 MPa in stay vane N°8.

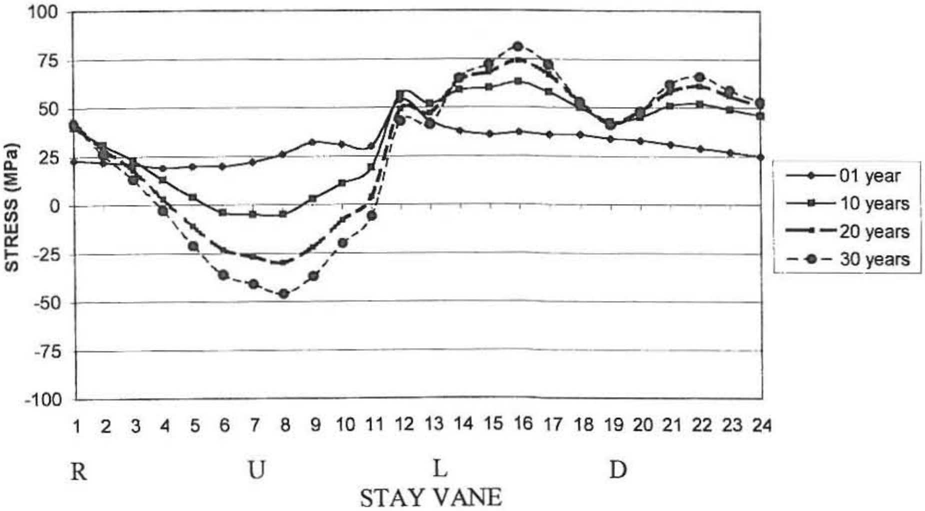


Fig.6 : Calculated vertical stresses at the stay vanes of PA III

REMEDIAL MEASURES

The mathematical models of Paulo Afonso I, II and III power plants are presently in the final stage of calibration, through comparison with the results supplied by some monitoring instruments already installed, and with measurement performed on electromechanical equipment. Once they are calibrated, these models will be used to investigate which remedial measures are the most efficient for mitigation of the problems caused by AAR on the generation equipment, which will consist, basically in the opening of the vertical expansion joints between blocks, and slotting of expansion joints between concrete and rock mass downstream the cave, above the draft tube.

CONCLUSION

The measures that are being carried out in the generation equipment of Paulo Afonso I, II and III powerhouses, since mid-eighties, when the problems related to Alkali-Aggregate Reaction in the Moxotó Hydroelectric Power Plant were diagnosed, are of great utility for the calibration of mathematical models. Because these equipment are installed inside the concrete structure of the powerhouse, they are exposed to the distortions caused by the concrete expansion, resulting from AAR, being therefore of great utility for the calibration of the Powerplants, where only a few monitoring instruments had been installed. However, the great advantage of having a good monitoring plan, which is going to be installed, is recognized for supervising the behavior of the Powerplants, in the long term, and the supervising the efficiency of the remedial measures to be implemented.

Cavalcanti et al. presented at this same Conference the results of the studies performed on the PA-IV hydroelectric Powerhouse about three years ago, and that are presently in the phase of retro-analysis, based on the results supplied by the instruments recently installed. When the studies of PA-I, PA-II e PA-III will be completed, the initial results of which were presented herein, it will be possible to compare the results of these four underground power plants equipped with 60 MW, 75 MW, 216 MW and 410 MW Francis turbines and to establish a correlation between the results of these models, in terms of tilting of turbine shaft, tensile stress in the distributor stay vanes, tilting of the turbine cover, etc., in order to become an important source of reference for underground powerhouses affected by AAR .

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