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MANAGEMENT OF STRUCTURES OF PETI DAM AFFECTED BY AAR

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ABSTRACT

PETI, a 1946 Hydroelectric Plant in Minas Gerais State, Brazil, on Santa Barbara River, has single curvature concrete arch dam (54-m length, 43-m height), founded in massive Peti Granite. Construction photos show efflorescence of calcium at horizontal lift joints, no cracking visible. In 1966, primary and progressive surface cracking was reported, chipped out and patched, reopening weeks after. In 1973, investigations defined left abutment geology and thrust block conditions by 3 vertical core borings and laboratory testing determined strength and characteristics of concrete, beginning a suspect of AAR. The stresses due to water load, dead weight, and differential temperature were recalculated using original design criteria: maximum compressive stress upstream face - cantilever stress 1,47 MPa (tension); arch stress 1,10 MPa (compression); downstream face - cantilever stress 1,53 MPa (compression); arch stress 1,38 MPa (compression); modulus of elasticity adopted 14.000 MPa. In 1997, evaluation indicated progress of cracking, shear off of top rail of safety handrail and dislocation of gates laterally making operation difficult. Efflorescence at all cracks on downstream face and staff additional field investigation as concrete coring; petrography and x-ray diffraction analysis of specimens; laboratory testing of strength; installation of instruments and mapping of cracking finally confirms AAR. The cracking observed in the vicinity of the left abutment thrust block has reduced load carrying capacity of the arch and safety factors, although still enough to guarantee the security of the Dam. Results are under analysis providing parameters of safety, evolution, and maintenance, leading the control plan and the project of restoration.

Keywords: AAR, Investigation, Management, Arch Dam, Monitoring

PROJECT LOCATION AND DESCRIPTION

The PETI Hydroelectric Development, completed in 1946, is located in State of Minas Gerais, Brazil, about 65 km east of Belo Horizonte. The Dam, constructed on the Santa Barbara River about 2 km upstream of its confluence with Brucutu Creek; pounds a reservoir with a surface area of about 4,25 km^2 and a volume of about 35 million m^3.

The Dam is a single curvature concrete arch with a crest length of 54 m and a maximum height of 43 m, as seen in Figure 1. The arch is abutted until each end of the dam by thrust blocks and cutoff wing walls. Flood discharges are passed by an overflow spillway, located on the crest of the Dam, which is controlled by six 5,5 m high by 6 m wide vertical lift gates. The elevations of the crest of the Dam and spillway ogee are 714 m and 707 m, respectively. The normal operating reservoir level, at the top of the spillway gates, is El. 712,5 m.

Fig. 1: Peti Dam in downstream view.

The two 4,500 kW turbine-generating units are located in a power house constructed downstream of the project in the Santa Bárbara River gorge at a point 1,3 km east of the Dam. The units are designed to develop a head of 74 m and are served by a 4 m diameter concrete lined power tunnel, 1200 m long, driven from an intake structure of the right abutment of the Dam. This structure is provided with trash racks and emergency closure gates. The sill of the intake structure is at El. 696 m. A surge tank, 8 m in diameter and 24 m height, is located in the flow line, about 1200 m downstream of the intake structure. The powerhouse is located about 100 m further downstream of the surge tank.

GEOLOGY OF THE SITE

The Dam and its associated thrust blocks are founded in a massive rock described as the Peti Granite. The location of the gorge formed during down cutting by the Santa Bárbara River is not considered to the geologically structurally controlled, also there is no available evidence of faulting or other geologic structure which could be related to the present course of the river. With the exception of right shore higher elevations faults or fractures were not reported in the excavation for the Dam foundations. Careful study of the excellent construction photographs of the project, which are maintained at the site, confirms that major faults or fractions do not cross the Dam foundation in the well keyed plug section at the base of the Dam or in the left abutment.

The right abutment is similarly sound up to El. 696 m. Heel of the thrust block excavation at El. 696,5 m was cut by a weathered shear zone about 20 m thick dipping about 45° upstream. This shear zone was exposed in the downstream wall of the excavation at about El. 702,5 m, where it intercepted a horizontal zone of decomposed and weathered material about 1 m thick. About El. 703,5 m the thrust block abuts a number of very large residual granite boulders measuring as much as 3 m by 3 m in cross section. These boulders are separated with seams of deeply weathered and decomposed materials. The seams tend to dip upstream at about 60° below horizontal and are from 10 to 30 cm thick. They are not seen blow the horizontal decomposed zone at El. 702,5 m. The abutment was over excavated attempting to improve the foundation conditions. A keyed addition was driven to a depth of 9 m along the decomposed zone between El. 702,5 m and El. 703,5 m and back filled with concrete.

The excellent quality of foundation obviated the necessity for other than the normal barring and wedging required to remove shot loosened materials to provide a sound undisturbed bedrock foundation for the project structures. Foundation grouting, either in a consolidation pattern or as a grouted cut-off curtain, was not performed. The extremely small amount of seepage water presently visible in the gorge downstream of Dam supports the lack of necessity for such work.

VISUAL OBSERVATIONS DURING INSPECTIONS FROM 1946 TO 1972

No unusual events were noted until November 4, 1948, when a moderate earthquake estimated to have an intensity of 4 (Richter Scale) was felt at the site. Later inspection reported that the Dam was undamaged and hadn't been affected by the earthquake.

Construction photos taken in late 1945 and early 1946, and studies at the site, show efflorescence of calcium sulfate and calcium carbonate at some horizontal lift joints in the Dam. However, no evidence of substantial cracking is visible in the early photos. In 1964, the plant operator reported perimetral horizontal cracks at the base of the surge tank. More studies were performed and concluded that the structure, which is founded on granite, was safe.

In 1966, the plant operator reported cracking of the Dam. The reported damage was described as being primarily surface cracking of certain piers and of the surface of the left abutment thrust block and wing wall. The plant operator serving at Peti since 1952 stated that the observed cracking has been progressive. He also noted that the top rail of the safety handrail had sheared off its supporting corner post at the downstream edge of the left thrust block. A few cracks in the top of the left thrust block were chipped out in 1966 and patched. The operator reports that these cracks reopened at the edges of the concrete patches within a few weeks after repair. The reservoir was first drawn down below El. 707,0 m during the dry period ending about December 1972. The operator reported cracks in the upstream face of the left abutment wing wall down to El. 702,0 m, the lowest level of draw down.

A new visual inspection of the project was made in January 1973 to determine the extent, probable cause or causes and possible remedial treatment of certain cracks apparent at the Peti Arch Dam; and additionally, to provide an analytical determination of the safety of the Dam in its present conditions. Based on the investigations performed, was recommended a field investigations program which was promptly authorized to thoroughly define the left abutment geology and thrust block conditions.

INVESTIGATIONS PERFORMED IN 1973

In October 1973, started the field investigation program which consisted mainly of: concrete coring of the left abutment by 3 vertical continuous core recovery borings, diameter 6 m, into concrete and bedrock.

- Laboratory testing to determine strength and material characteristics of thrust block concrete;
- Installation of extensometers in the drilled holes (not installed).

The main results obtained can be resumed as (Kihara, 1973):

- Average compressive strength 34,9 MPa
- Average modulus of elasticity (static) 14,200 MPa
- Average modulus of elasticity (dynamic) 23,575 MPa

ARCH DAM STRESS ANALYSIS

The stresses in the Dam due to water load, dead weight, and a temperature differential of 18° F were recalculated in 1973 utilizing an EBASCO developed computer program described as the "Multiple Cantilever Method". This method, which uses an approach similar to the well known "Trial Load Method", of the U S Bureau of Reclamation divides the arch dam into horizontal and vertical structural elements which may consist of as many as ten arches and seven cantilevers. The distribution of load between the arch and cantilever systems is determined by equating the radial deflections due to unit loads at the points of intersection and solving the system of simultaneous equations for unit load coefficients. The compatibility of arch and cantilever deflections is determined projecting all radial deflections onto the plane of the cantilever section.

The results of this stress analysis, using original design criteria regarding material characteristics are shown in Figure 2 (a). Figure 2 (b) shows the results of the stress analysis given in the Peti H E Development Design. As would be expected, the more sophisticated analysis, which considers cantilever action of the structure, results in lower stresses than the original, conservatively calculated, values. Additionally, a stress analysis utilizing a lower elastic modulus for the left half was also performed. The results shown in Figure 2 (c) indicate a general increase in stress levels at the left side however the newly calculated stress levels are still lower than the original allowable design stresses.

The main results of this stress analysis using the original design criteria regarding material characteristics (Maximum Stresses):

- Left Abutment

	• Upstream face	- Cantilever stress	0,48 MPa (tension)
		- Arch stress	0,51 MPa (compression)
	• Downstream face	- Cantilever stress	0,49 MPa (compression)
		- Arch stress	1,26 MPa (compression)
- Arch Dam			
	• Upstream face	- Cantilever stress	1,46 MPa (tension)
		- Arch stress	1,29 MPa (compression)
	• Downstream face	- Cantilever stress	1,53 MPa (compression)
		- Arch stress	1,38 MPa (compression)

COMPLEMENTARY INVESTIGATIONS PROGRAM EXECUTED IN 1997

In 1997, a new evaluation of the Dam situation was performed and concluded that the observed cracking has been progressive and the top rail of the safety handrail had sheared off in different points. Additionally, the gates were dislocated laterally creating difficulties during their operation. Also was observed efflorescence of calcium sulfate and calcium carbonate at all cracks on the downstream face of the left abutment evidencing an advanced alkaline reaction in the concrete structure of left abutment. CEMIG decided to make additional field investigation program consisted of (Silveira, 1996):

- Concrete coring of the left abutment and central portion of the Dam;
- Petrography analysis of concrete specimens (Pacelli, 1997);
- Laboratory testing to determine strength to concrete (Ferreira, 1997);
- Installation of extensometers and other instruments, as shown in Figure 3.

The main results obtained can be resumed as:

- Left Abutment

• Average Compressive Strength	17,8 MPa
• Average Modulus of Elasticity (static)	14.000 MPa
• Poisson	0,15 to 0,30

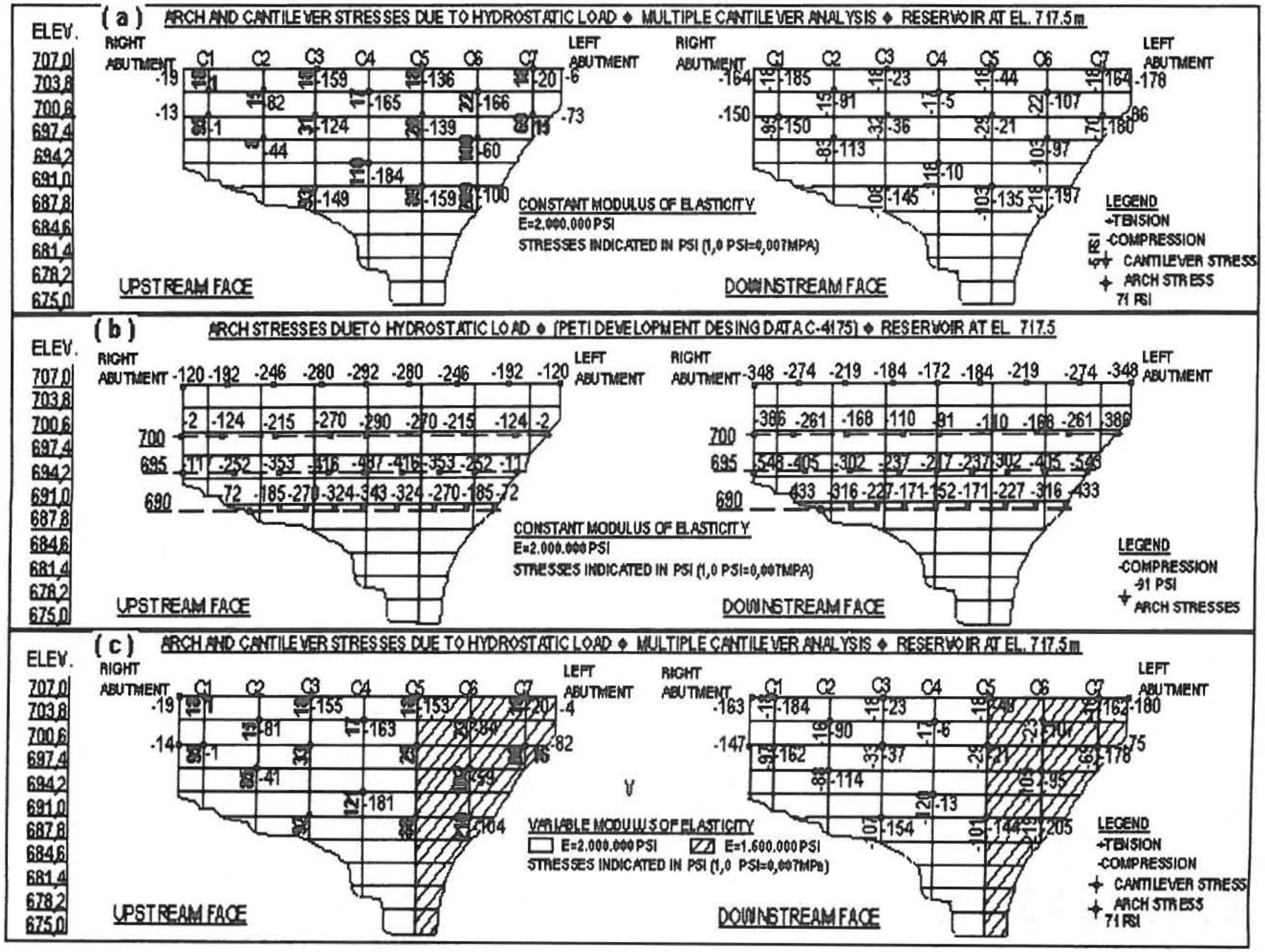

Fig. 2: Results of stress analysis.

- Arch Dam

- Average Compressive Strength 22,8 MPa
- Average Modulus of Elasticity (static) 17.000 MPa
- Poisson 0,16 to 0,36

It can be observed that concrete strength indicated lower values at the left abutment compared with the arch dam. This fact confirms the more advanced attack of AAR in the left abutment.

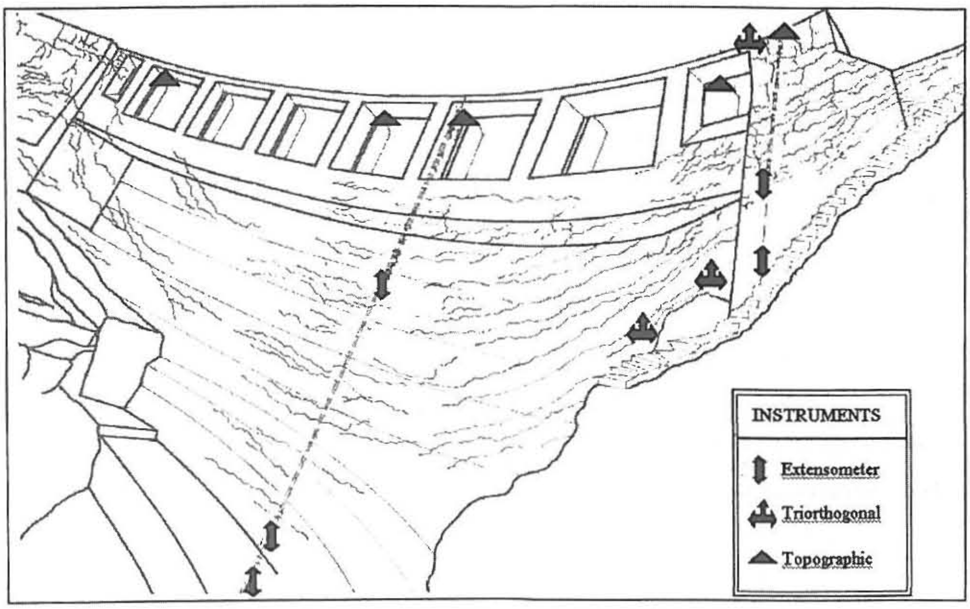

Fig. 3: Instrumentation installed for surveillance.

CEMIG staff and consultants analyze results of investigations, as follows.

ENGINEERING ANALYSIS

In order to evaluate the present arch dam and left abutment block stability, a resume of the results/analysis done is shown in Table 1.

Items 3 and 4 on Table 1, shows the values of safety factors in 1973 and 1997 respectively, and item 5 shows the ratio between both. It can be observed that the evolution of the safety factors are being reduced from 1973 to 1997 by almost 50% in the left abutment and 33% in the arch dam, although the values calculated in 1997 indicates that the structure is still safe.

TABLE 1: Resume of Results / Analysis

ITEM	DESCRIPTION		LEFT ABUTMENT	ARCH DAM
1	**Concrete resistance stresses at 1973:**			
1.1	Compressive strength	(MPa)	34,9	(34,9) *
1.2	Tensile strength	(MPa)	(3,49) **	(3,49) **
1.3	Modulus of elasticity	(MPa)	14200	(3,5)
2	**Concrete resistance stresses at 1997:**			
2.1	Compressive strength	(MPa)	17,8	22,8
2.2	Tensile strength	(MPa)	(1,78) **	(2,28) **
2.3	Modulus of elasticity	(MPa)		
3	**Factors of Safety at 1973:**			
3.1	Compressive strength	(MPa)	27,7	(22,9)
3.2	Tensile strength	(MPa)	(7,2)	(2,4)
4	**Factors of Safety at 1997:**			
4.1	Compressive strength	(MPa)	14,1	15,0
4.2	Tensile strength	(MPa)	(3,7)	(1,6)
5	**F.S. 1997/F.S. 1973**			
5.1	Compressive stresses		0,51	0,66
5.2	Tensile strength		0,51	0,67

* No investigations were made in the arch dam in 1973. Therefore were considered in this analysis the results obtained for the left abutment.

** No laboratory investigations were made do determine the concrete tensile stresses. For this analysis we adopted 10% of the compressive stresses.

CHEMISTRY AND PHYSICS CHARACTERISTICS

As explained in the "Solution Theory" by Paulon and Visvesvaraya et al. (Pacelli, 1997), for the alkali-silicate reaction that occurs in Peti Dam: a thin adherent layer develops around the agregate when the concrete is still new. As time go by, in wetly conditions, Ca $(OH)_2$ from the concrete mixture reacts with feldspar; lime can invade the aggregate, reacts and set alkali free as KOH and NaOH; this last one is a gel partially soluble in water; as soon as the alkali proportion reaches certain density, the calcium silicate, as adhesion, tend to dissolve in potassium and sodium silicates, usually as gel around and inside the aggregate; this material is partially soluble in water and a very bad cohesion element, contracting and expanding as it loses or gets water; finally, the particle involved by this semi-liquid has low resistance.

All those conditions occur in the Peti concrete. The alkali proportion is 1 % or 3,5 kg/m^3 as the cement proportion is 350 kg/m^2. It is considered high by our concrete lab (Ferreira, 1997). The water/cement coefficient = 0,60 is also too high as 0,43 or less is enough to make a good concrete. So, there was enough water for the reaction since the beginning of the construction. The aggregate is reactive too: deformed quartz is present, and its waving extinction angle is higher than 40 degrees. Those characteristics lead to the expansion rates estimated in the last 50 years that follows: 20 x 10^{-6} micro-deformations/year in the right abutment and in the middle of the arch, 120 x 10^{-6} micro-deformations/year in the left abutment. The difference is explained by construction conditions: builders exposed the last referred structure to maximum loads at young age. The instrumentation installed in 1997 show in Figure 4 that the expansion continuous but in short rates: 8,9 x 10^{-6} deformations/year in the middle of the arch, 65,3x10^{-6} deformations/year in the left abutment. The result reveals a considerable to great expansion rate in comparison with other dams around the world, as seen in congress reports.

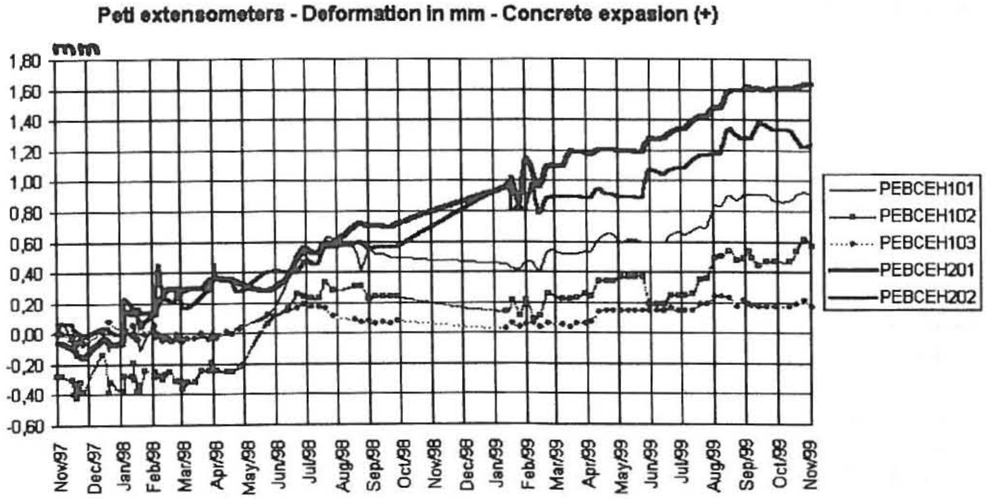

Fig. 4: Extensometers data graphics.

CONCLUSIONS

Based on the evaluation of the results of analysis and investigations performed the following conclusions have been reached:

1. The Peti Dam has suffered mild to moderate damage concentrated in, but not confined to, a general area localized on the left abutment between elevations 695 m and 705 m.

2. The observed cracking of the dam is mainly due to Alkali Aggregate Reaction. Other possibilities studied, as sulfate attack, carbonate drainage, foundation movement, etc., are not present or are insufficient to cause it.

3. The cracking observed in the vicinity of the left abutment thrust block has reduced the load carrying capacity of the arch and the safety factors have consequently been reduced as described above.

4. Although safety factors values are still sufficient to guarantee the security of the dam, it is recommended that continuous laboratory testing to determine strength of concrete and safety factors should be made at least each 3 years. A new test will be made in the late 2000.

Finally, CEMIG technical staff and their consultants are studying to define the best technical and economical solution to be applied to guarantee the security of the Dam. The solution adopted will be presented during the conference, if available. The deadline to the repairs is defined after results of monitoring, as soon as safety factors pass limits under discussion at the moment.

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