Diagnosis of Songloulou Dam:
Innovative stress measurement on concrete abutment

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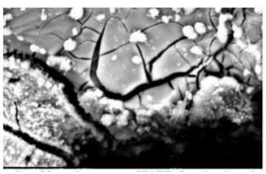
Introduction

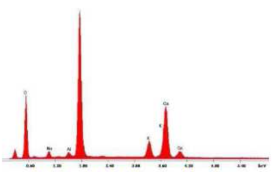
The Songloulou dam is built on the Sanaga River in Cameroon. It has a drainage area of 130,000 km, an interannual modulus of 2000 m^3/s and the following flood flow characteristics: Q_{10} = 7400 m^3/s, Q_{100} = 8000 m^3/s, $Q_{1\,000}$ = 8890 m^3/s and $Q_{10\,000}$ = 9830 m^3/s. With an installed capacity of 384 MW, it is the main hydroelectric scheme of Cameroon. The owner is AES- SONEL.

Figure 1: photography of the dam (source: Cameroon-infor.net)

Concrete swelling phenomenon have been identified six years after the commissioning of the first groups (1981) through the reduction of gaps between stationary and movable parts of turbines and alternators. Since, swelling lead to various problematic consequences for the operation and safety of the structures: cracks, difficult handling or even blockages of valves, cofferdams spillway and water intake, deformation of stationary parts...

Laboratory tests conducted by IFSTTAR between 2009 and 2011 on concrete sample have confirmed that the Songloulou dam suffers from severe disease (alkali reaction) resulting in a swelling of the material.





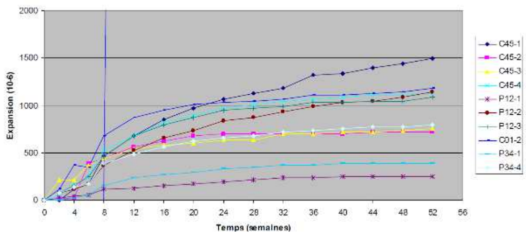


Figure 2: Fracture surface of a sample: reaction product having an amorphous morphology and a sand-calc-alkaline composition and residual expansion measured on 10 samples taken from the dam (source: IFSTTAR)

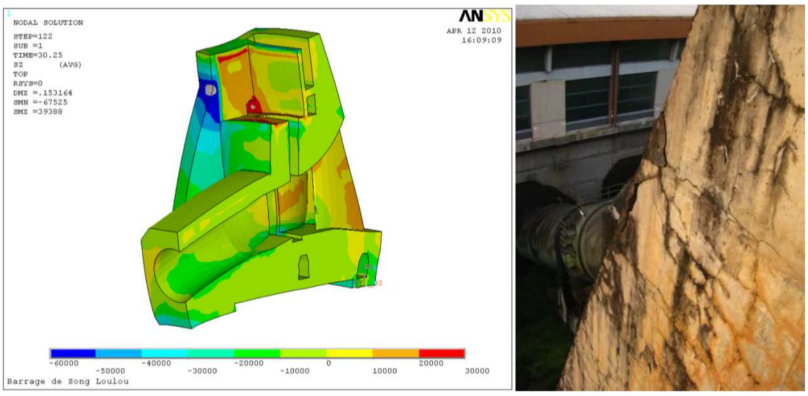


Figure 1: Stress modeling (Source: ISL)

In 2012, AES SONEL has wished to determine in situ mechanical stresses caused by the concrete swelling (alkali-silica reaction). Cementys offered its expertise in the field of in situ stress measurement in concrete by the method of core drilling. This method, widely used for metal (standard method ASTM E837), allows to determinate, punctually and directly, the plane stress state in a structure.

1. Methodology for the determination method of in situ stresses

The InsideStress method developed by Cementys allows to determine experimentally the mechanical plane stress state in a structure by measuring local strains generated during the microcavity drilling (method called "incremental hole"). The InsideStress method is based on a double Cementys expertise in terms of instrumentation (microforage and in situ strain measurements by vibrating wire sensors) and mechanical measurements interpretation.

Using the in situ stress measurement technique and the associated analysis, the InsideStress methodology provides directly to the client:
• The stress state of the auscultated element (directions and principal stresses: plane stress tensor of three components XX, YY, XY)
• An indication of the stress evolution in the depth of the element

For both concrete and masonry structures, InsideStress uses the method on the incremental coring instrumented by MicroVib 54 vibrating wire sensors. When the stress is uniform in the depth of the core, the stress state is directly obtained from the knowledge of homogenized elastic properties of the material (Young's modulus and Poisson's ratio).

In the case of high mechanical stresses, a non-linear calculation can take into account the effect of material local damage.

A comparison of the coring and flat jack techniques is synthesized in the following table:

Technique	Coring	Flat jack
Applicable standards and recommendations	Standard for rocks ASTM D4623 – 08	Recommendations RILEM TC 177-MDT
Measuring principle	Stress relief of a drilled test	Release and reloading a slot- flat jack
Measurement Type	Direct by releasing	Indirect discharge/charge
Multi-axiality	Measurement of the plane stresses (XX, YY, XY)	Dimensional measure (XX)
Normal / shear stress	Full strain state (normal and tangential)	Dimensional normal stress
Measuring time	40 minutes for a drilling Diam400mm	60 minutes for masonry 120 minutes for the concrete
Accuracy strain	1 micron/meter with vibrating wire sensor MicroVib	10 micron/meter with retractometer ball and Compare micron
Accuracy constraint	0.1 MPa in all directions with the module known to within 5%	0.5 MPa with known modulus to within 5%
Intrusiveness	Low : Diameter 200mm mini, 400mm max	High: 50cm slit, 5mm thick
Possible artifacts	The effect of drilling water on the auscultated material (swelling potential if the released test specimen is too small)	Disruption of masonry under the action of the discharge/charge Stiffness different between the discharge and recharging Geometric calculation problem of stress from the pressure of the flat jack (flat jack slot geometry and geometry)
References	http://science.uwaterloo.ca/~mauriced/earth437/requiredreading/assignment_2_readingStress/Eberhardt_L4-InSituStress.pdf http://www.civil.iitb.ac.in/~dns/IACMAG08/pdfs/O44.pdf « Rock Stress and Its Measurement » B. Amadei, O. Stephansson – 1997 « In-situ stress determination used in structural assessment of concrete structures ». A. Owens, Strain 0/2008; 29(4):115 - 124	

Table 1: comparison of the coring and flat jack techniques

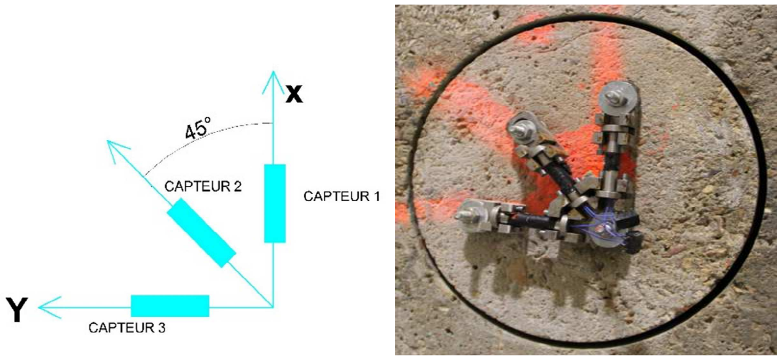


Figure 4: Local frame of the sensors

Strains are measured by the sensors in the local frame formed by the three sensors. Then the stresses are determined using the elastic properties of the materials by the following equations:

$$\sigma_1 = \frac{E}{1-\nu^2} \cdot (\varepsilon_1 + \nu \cdot \varepsilon_3)$$

$$\sigma_3 = \frac{E}{1-\nu^2} \cdot (\varepsilon_3 + \nu \cdot \varepsilon_1)$$

$$\sigma_2 = \frac{E}{2+2\cdot\nu} \cdot \varepsilon_2$$

The Young's modules E and Poisson's ratios ν are experimentally determined by using concrete specimens taken in situ at the site of Songloulou.

The principal directions form an orthonormal basis on which the tensor can be represented as below:

$$\tilde{\sigma} = \begin{pmatrix} \sigma_{xx} & \sigma_{xy} & 0 \\ \sigma_{xy} & \sigma_{yy} & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad \tilde{\sigma} = \begin{pmatrix} \sigma_I & 0 & 0 \\ 0 & \sigma_{II} & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

The principal stresses associated with the new frame is obtained by calculating the eigenvalues of the 3x3 matrix:

$$\sigma_I = \frac{E}{1-\nu} \cdot \frac{\varepsilon_1 + \varepsilon_2}{2} + \frac{E}{\sqrt{2 \cdot (1+\nu)}} \cdot \sqrt{(\varepsilon_1 - \varepsilon_2)^2 + (\varepsilon_3 - \varepsilon_2)^2}$$

$$\sigma_{II} = \frac{E}{1-\nu} \cdot \frac{\varepsilon_1 + \varepsilon_2}{2} - \frac{E}{\sqrt{2 \cdot (1+\nu)}} \cdot \sqrt{(\varepsilon_1 - \varepsilon_2)^2 + (\varepsilon_3 - \varepsilon_2)^2}$$

The principal direction relative to the X axis is calculated by:

$$|\sigma| = \arctan\left(\frac{2 \cdot \varepsilon_2 - \varepsilon_3 - \varepsilon_1}{\varepsilon_3 - \varepsilon_1}\right)$$

2. Results and conclusions

6 in situ stresses measurements have been performed by the method of InsideStress on 3 buttress (buttress 2, 4 and 7, from the left bank to the right bank), or 2 measurements on each side of the buttress studied.

Figure 5: Position of measuring points

The concrete elastic properties are the basis for the determination of in situ stresses in the buttress of the hydroelectric scheme of Songloulou:

• Poisson's ratio in the range [0-0.5]
• Relatively low Young modulus (<20 GPa) in the case of a structure reached by alkali-reaction.

	point 1	point 2	point 3	point 4	point 5	point 6
Module d'Young (E) en GPa	19.3	10.8	12	16	11.3	12.7
Coefficient de Poisson (ν)	0.29	0.08	0.06	0.16	0.13	0.15

Table 2: Concrete elastic properties (measured in the laboratory)

In situ stress values are relatively low due to the concrete low young modulus, but they are representative of the stresses in the released core, for an average depth of 20 cm.

	Point 1	**Point 2**	**Point 3**	**Point 4**	**Point 5**	**Point 6**
Direction principale φ(°)	74	83	34	75	133	129
Contrainte principale 1 (Mpa)	0.2	1.7	1.6	0.8	1.7	2.6
Contrainte principale 2 (Mpa)	-0.6	0.0	-4.2	-1.1	-0.9	-0.9

Table 3: Principal directions and principal stresses

It is worth noting that the behavior of the buttress 2 and 4 are similar. In fact, these two buttresses present unusual principal directions on right bank and coherent on left bank.

The results of the buttress 7 are consistent with those expected, moreover, the principal directions are similar to items 5 and 6.

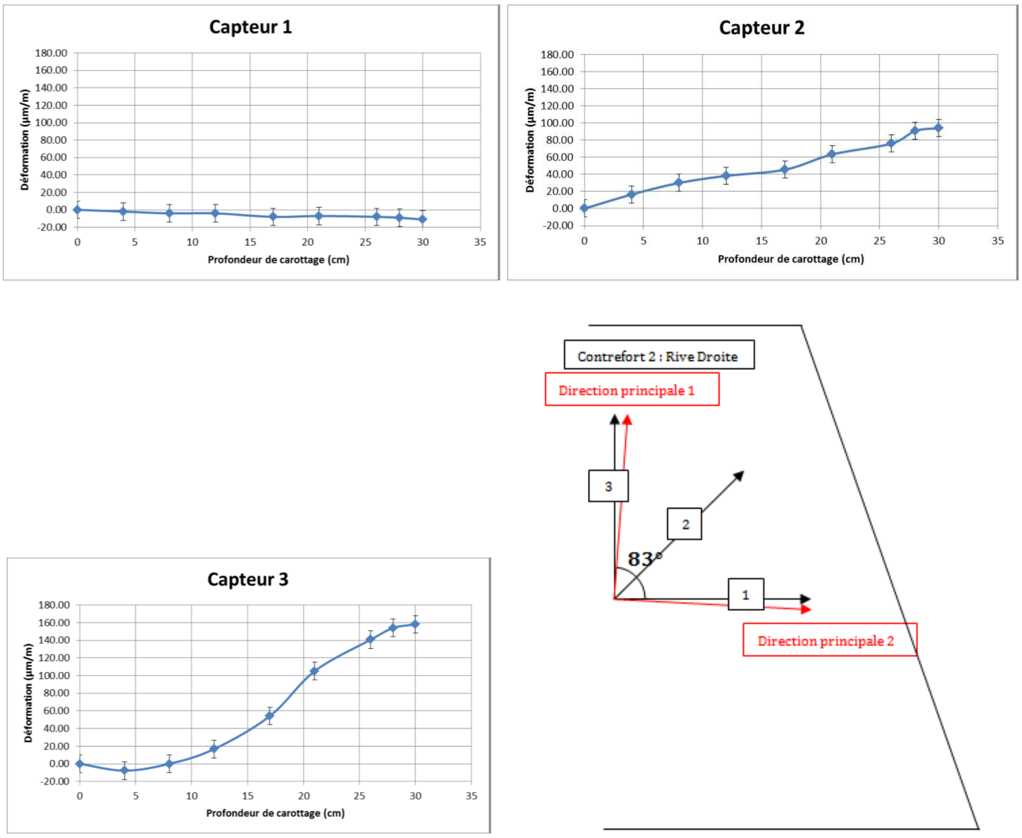


Figure 6: Example of calculation - buttress 2 (right bank)

References

[1] **ASTM E837**, Standard Test Method for Determining Residual Stresses by the Hole-Drilling Strain-Gage Method, ASTM International, West Conshohocken, PA, 2013

[2] **ASTM C215-02**, Standard Test Method for Fundamental Transverse, Longitudinal, and Torsional Frequencies of Concrete Specimens, ASTM International, West Conshohocken, PA, 2002

[3] **ASTM E1876-01**, Standard Test Method for Dynamic Young's Modulus, Shear Modulus, and Poisson's Ratio by Impulse Excitation of Vibration, ASTM International, West Conshohocken, PA, 2001

[4] **T. Guillemot, M. Lino, E. Nzalli**, Diagnostic et mise en sécurité du barrage de Songloulou au Cameroun vis à vis des désordres liés à l'alcali-réaction, Colloque CFBR Modernisation des barrages, Chambéry, 2013 (in French).