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In Situ Test of a Borehole Extensometer

By

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Summary

Stresses in the Earth's crust are known to represent a key element of geodynamical processes at various spatial and temporal scales. Static stresses within lithospheric plates can be estimated on the basis of direct in situ measurements in boreholes or near the surface. Earthquake focal mechanisms yield the same type of information by sampling at greater depths. The quantification of geological deformations happens to be the principal tool to determine possible changes in time of the tectonic stress pattern. These changes can however be recorded only qualitatively and on the geological time scale.

In seismic regions it is clear that the regional stress field varies on a time scale defined by the recurrence of earthquakes, say several tens of years. Our goal was to design a robust and cheap instrument which could continuously monitor stress changes at depths large enough to reduce meteorological influences.

Description of the Extensometer

The starting idea was to measure possible elastic deformations within a deep segment of a vertical borehole. To achieve a good sensitivity it was clear that one should measure changes in the length of this segment, rather than in its diameter. Fig. 1 sketches both end pieces of the instrument, which have to be sealed separately to the walls of the borehole. They are connected through a 5 meter long invar wire (1), which was specially treated to avoid long term creep. A weak PVC tube (2) protects this wire and contains an oil of density larger than that of water, which protects the whole inside against corrosion. A metallic disc (3) is attached at the lower end of the invar wire which is kept under a tension of 100 Newtons by a spring (4). At the upper end the wire is attached through a micrometric screw device (5). The latter allows to carry out a controlled vertical displacement of the disc. A variation in the stresses applied to the surrounding rock mass will also induce a displacement of the disc relative to the lower end piece. The two coils (6 and 7) are fixed to that lower end piece. Their inductance depends upon the position of the metallic disc. This property is used in order to monitor changes in the length of the borehole segment containing the extensometer. A platinum wire thermometer (8) is mounted close to this coild detector.

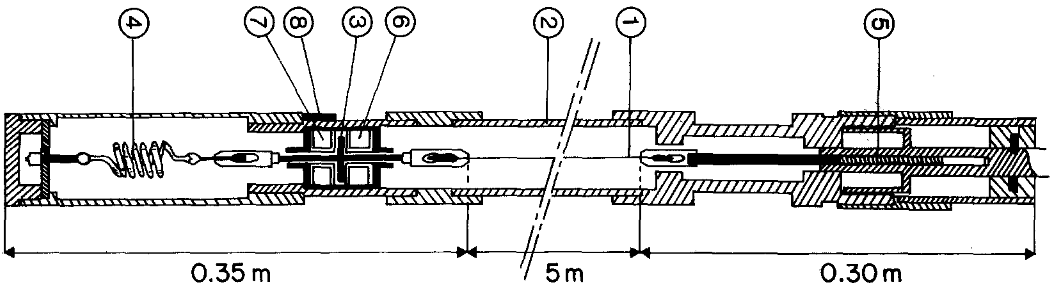

Fig. 1. Schematic cross-section of both extremities of the extensometer. The left corresponds to the bottom, the right to the top of the instrument. The 5 meter long central part is left out. Other dimensions are drawn to scale. As described in the text the metallic disc (3) is rigidly attached to the upper end piece through an invar wire (1). It can slide vertically between the two coils (6) and (7) of the detector when the length of the extensometer which is sealed to the surrounding rock happens to vary. Such a relative displacement can be produced for calibration by turning the micrometric screw (5) which is not described in details in this sketch. The head of this screw can be operated through a rigid rod from the top of the borehole. This rod is not shown in the diagram, nor are the ball bearings guiding the disc assembly through the central hole of the detector. The platinum wire thermometer (8) is mounted next to this coil detector. The case of each end piece is made of steel, but the long protection (2) is a soft PVC tube, filled with oil

Fig. 2 is a schematic description of the monitoring system connected to the two-coil detector. It shows that an electrically controlled switch can alternately couple each coil to a capacitor. The resonance frequency of each LC circuit is around 10^5 Hz. It is measured at prescribed time intervals, as is the temperature next to the detector. These observations are recorded. The preamplifier is mounted in the lower part of the extensometer, whereas the monitoring system with its power supply, clock, frequency meter and recorder is kept at the surface.

Careful tests of a prototype, where the 5 meter long PVC tube (2) was replaced by a shorter rigid metallic tube, were first carried out in the laboratory. The full size instrument was than sealed in a borehole made available by the electric board EDF and located beneath the Laouzas dam in southern France. The idea was to make use of natural excitations of the rock massif by seasonal changes of the water level. Fig. 3 depicts a cross-section of the dam with the extensometer borehole drilled beneath the lower tunnel, the monitoring system being installed in the upper tunnel. This section also shows the location of some permanent extensometers installed by EDF to control the mechanical behavior of the dam close to our instrument. Typical water level variations have an amplitude of about 10 meters, particularly during winter. The response of the dam was known to be quite complex as it also includes a deformation induced by seasonal temperature changes of the concrete structure. In particular the dam will

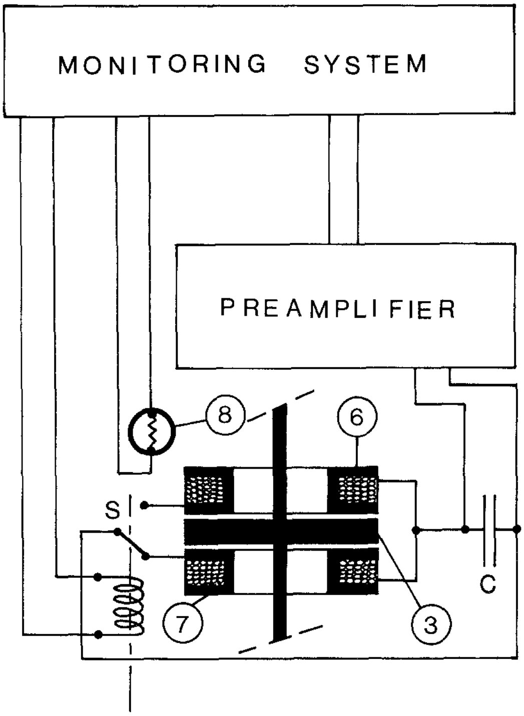

Fig. 2. Block diagram of the two-coil detector, which is mounted with a preamplifier in the bottom end of the extensometer described in Fig. 1. The monitoring system excites the two LC circuits made up of the capacitor C alternatively connected to each coil (6) and (7) through the electro-magnetic switch S. Like in the previous Figure, (3) is the mobile metallic disc which affects the resonance frequencies of both LC circuits. This sketch is not to scale: the disc has a diameter of 5 cm, a thickness of 0.3 cm and can move vertically 0.18 cm away from the central position shown here. The thermometer (8) is shown again

tilt in the downstream direction when the water level rises. In Fig. 3 this is indicated by two arrows. Such a tilt is also produced when the curved dam structure cools and contacts perpendicularly to the section drawn on the Figure.

The micrometric screw at the upper end of the extensometer can be turned from the head of the borehole. This changes the disc position in the coil detector and yields an in situ calibration of the instrument, which turned out to be identical with the calibration obtained in the laboratory. Fig. 4 displays the in situ calibration, which was repeated annually from 1983 to 1986 and remained constant. It represents the difference in resonance frequency ν between the two LC circuits, including either the upper or the lower coil of the detector, for different positions of the metallic disc around the central one. The two symbols depicting upward and downward displacements of the disc show some mechanical hysteresis, i. e. back lash for the micrometric screw. The straight line through the data points has a slope of $9 \cdot 10^{-8}$ m/Hz. Considering the fact that the length of

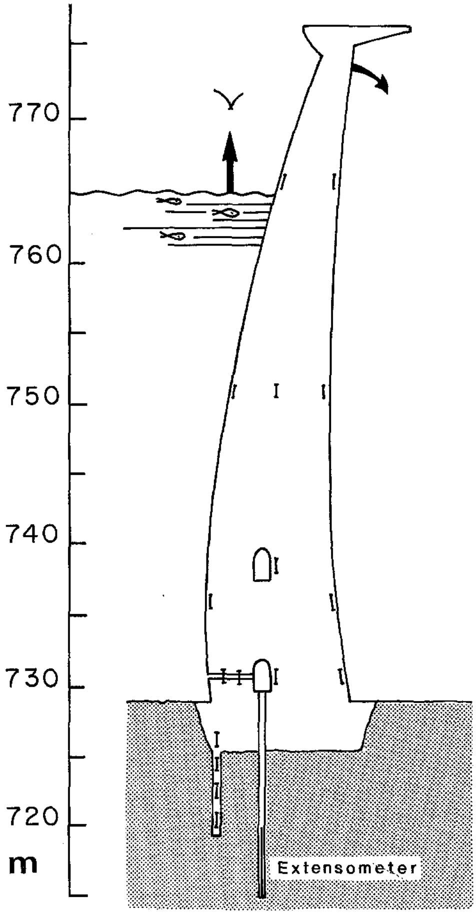

Fig. 3. Cross-section of the concrete dam of Laouzas with a scale of the altitude above sea level given in meters. The borehole in which the extensometer was sealed is beneath the lower tunnel. Its diameter, about 10 cm, is not drawn to scale. Another borehole is visible, and contains four smaller size extensometers. Other devices used by the electricity board and embedded in the concrete structure are also indicated. The dam closes a 300 meter-broad V shaped valley. The extensometer lies beneath its center portion. The two arrows depict an increase of the water level and the direction of the tilt this induces

the invar wire is 5 meters and that $\Delta \nu$ is measured with a precision ± 1 Hz, this calibration shows that our instrument should detect deformations as small as $4 \cdot 10^{-8}$. This sensitivity is just insufficient to detect Earth tides which could also represent a useful signal for calibration. The absolute accuracy of the instrument is much more difficult to quantify, as no simple repetitive loading experiment can be carried out in situ.

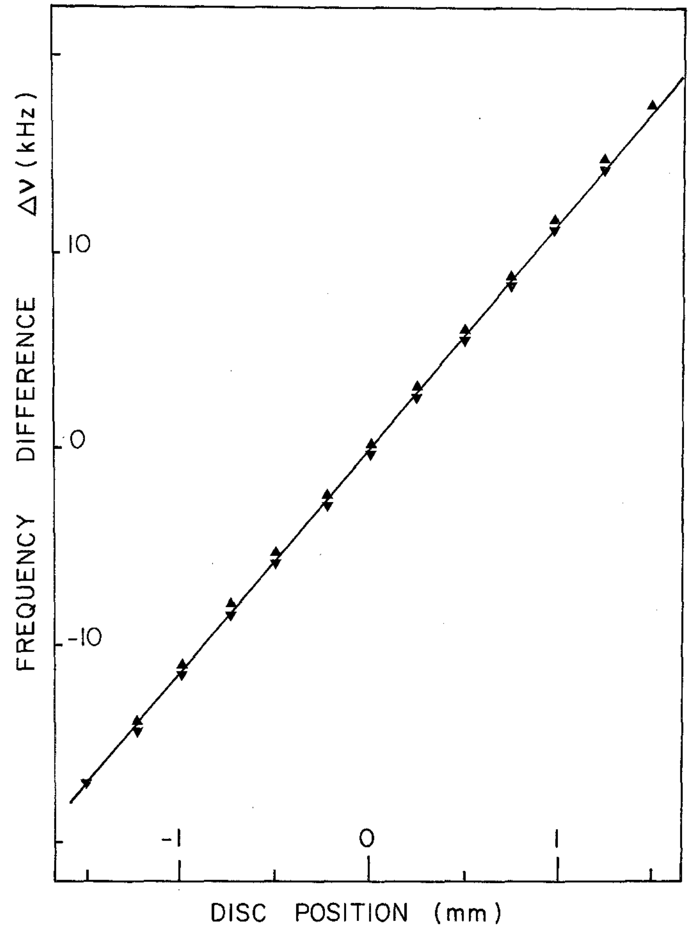

Fig. 4. Calibration curve showing the measured difference $\Delta\nu$ between the resonance frequencies of the two LC circuits of the detector described by Fig. 2. This quantity is plotted vs. position of the metallic disc (3) away from the center between both coils. The small hysteresis is caused by some back lash in the micrometer device (5). The above numbers in brackets refer to Fig. 1

Presentation of the Recorded Data

The simplest excitation of the dam-rock system around the extensometer is connected to changes in the water level in the lake. These changes are plotted in Fig. 5 for a period of time — March 1986 to July 1988 — during which the extensometer has been continuously recording. The lake level is kept constant during summer for vacational activities, and the effects of water withdraw and rainfalls create the strong oscillations during the other seasons. The vertical scale represents the water level above sea level. The amplitude of the oscillations are thus close to 10 meters, i. e. 1 bar of vertical loading.

Changes in temperature constitute another possible excitation. Fig. 6 shows the recorded temperature variations in four locations. Curve *a* derives from a thermometer mounted within the top of the dam, well above the surface of the lake: it corresponds to the smoothed temperature of the atmosphere. Curve *b* refers to the water near the lake bottom. It describes slow temperature increases followed by rapid decreases. Curve *c* is taken from a thermometer in the lower tunnel (see location in Fig. 3) and thus reflects the temperature inside the base of the dam. Finally, curve *d* was recorded by our platinum wire thermometer placed 15 meters below the head of the borehole. This last curve is drawn with respect to a dilated

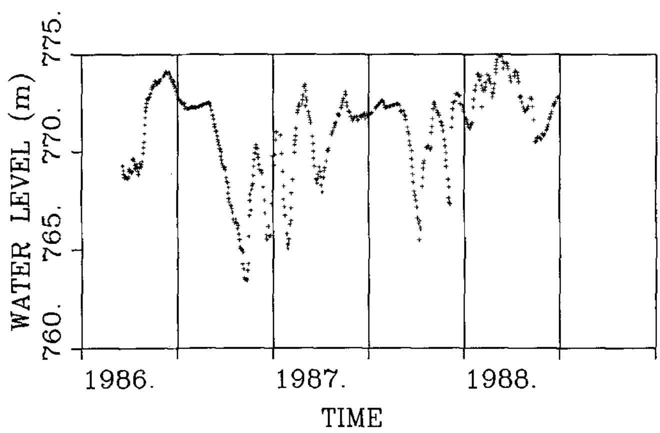

Fig. 5. Water level vs. time. The vertical axis is in meters above see level, like in Fig. 3. The time scale starts on January 1st, 1986, and ends on December 31st, 1989

temperature scale shown on the right hand side of the Figure, as the peak to peak amplitude is here only 0.2 °C. Contemplating the 4 curves one notices that the amplitudes decrease and the phases are delayed as one samples deeper and deeper parts of the structure. At the lower end, only the annual period stands out. Simple one-dimensional conductive calculations based on this observed amplitude and phase at 15 meters depth (curve *d*) show that a source near the concrete rock interface with temperature variations equal to those of the deep water (curve *b*) would be consistent with observations. One knows indeed that water is infiltrating the contact between the dam and the country rock.

Fig. 7 depicts, for the same period of time, the recorded deformation expressed in terms of the measured difference $\Delta \nu$ in resonance frequencies of our detector. It is dominated by an oscillation with annual period. The sharp jump after June 2nd 1986 is caused by the last calibration. It is followed by a relaxation transient lasting several days, after which the instrument seems to be stable again.

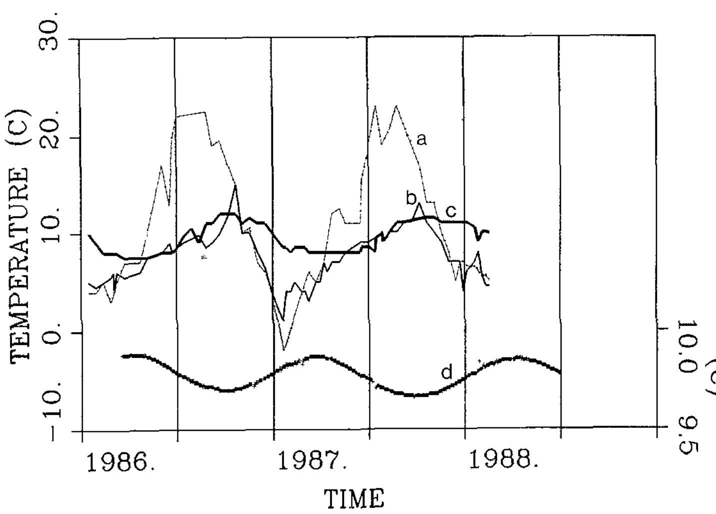

Fig. 6. Temperature vs. time at four different locations within the cross-section shown in Fig. 3. Curves *a*, *b*, and *c* were provided by the electricity board and refer to the temperature scale on the left of the frame. They represent a data set with unknown accuracy and variable sampling period. Curve *d* derives from our thermometer with one data point every day, although six measurements were available per day. For this last curve, the temperature scale is expanded and drawn on the right of the frame. The step-like appearance is caused by the limited accuracy of our monitor (0.01 °C). The odd points are caused by external power failures

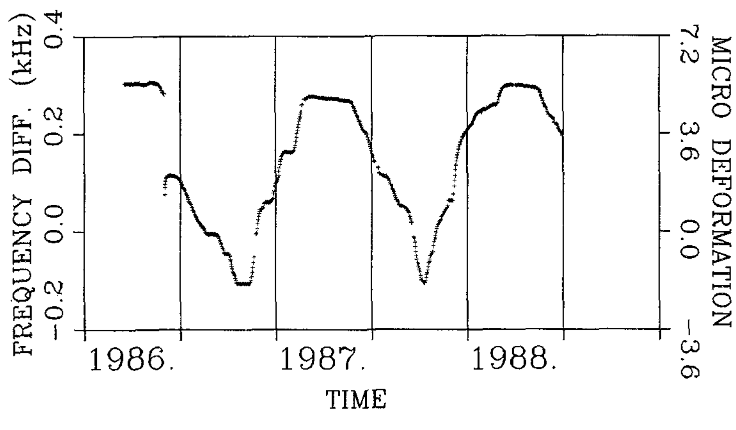

Fig. 7. Recorded frequency difference $\Delta\nu$ for the same period of time as in the two previous Figures. The vertical scale on the left hand side is in kHZ. On the basis of the calibration given in Fig. 4 this vertical scale is expressed as a deformation on the right hand side of the frame. The zero is arbitrary for both scales

Analysis of the Observed Deformation

In order to make sure that this test is meaningful we will try to relate the response of the extensometer (Fig. 7) to the two obvious excitations: water level variations and temperature effects on the dam structure and the rock beneath it (Figs. 5 and 6). The recorded deformation is dominated by a large amplitude variation with an annual period, but higher frequency components are also visible. The annual periodicity is also characteristic of the four temperature curves, but does not stand out so prominently in the water level graph. When the phases of the possible excitations are compared with that of the annual cycle of the deformation, one sees immediately that only the temperature variations registered inside the base of the dam and near the extensometer could possibly be in the correct phase. It turns out that the average temperature variation of the rock surrounding the instrument has an amplitude of 0.25 °C. This value derives from the measured amplitude of 0.1 °C at the lower end of the extensometer, and from upward extrapolated values by means of the diffusion law. This leads to a thermal expansion of the rock which only accounts for one half of the observed deformation. The other half is therefore to be attributed to an indirect effect: the tilt of the dam caused mainly by thermal changes at its base. In short, a temperature increase around the instrument will expand the rock, but at the same time there is a temperature decrease at the base of the dam, which contracts itself and tilts in the down stream direction. This last motion unloads the rock mass near the valley center, in which the borehole is drilled. Such a scenario is consistent with previous findings of the engineers in charge of the dam.

Direct or indirect effects connected to changes in water level are best seen if this excitation and the induced deformation are filtered, by standard Fourier transform, in order to separate the shorter periods. Fig. 8 depicts these two quantities for periods equal or shorter than 50 days. The similarity of the two curves is very striking. However the sign of the recorded deformation yields an apparent paradox: When the water mass increases, the length of the borehole axes also increases! Here again a downstream tilt of the dam unloads the rock near the borehole. This tilt is now induced mechanically, rather than thermally. This complex behaviour is consistent with the readings of the other instruments shown in the second borehole of the cross-section drawn in Fig. 3. It turns out that the negative effect caused by the tilt of the dam is about thrice the magnitude of the direct contribution of vertical water loading. This statement takes account of the known calibration of our instrument and of an estimated value of the Young modulus of the granitic basement. The sensitivity of our deformation readings (±1 Hz) is such that a change in water level by 10 cm is detectable. The recorded signal must therefore also contain possible components of the deformation linked with large changes in the atmospheric pressure. We have not attempted to extract this weak component.

In conclusion this first in situ test, which lasted several years has shown the excellent mechanical stability of the instrument and of its attachment to the walls of the borehole. The sensitivity is such that deformations equal to $4 \cdot 10^{-8}$ are detectable. For a rock mass with an elastic modulus equal to $5 \cdot 10^{10}$ Pa, this means that stress changes larger than 2000 Pa (0.02 bar) can be monitored. This should be adequate in seismic regions. There however one would like to reduce the annual direct

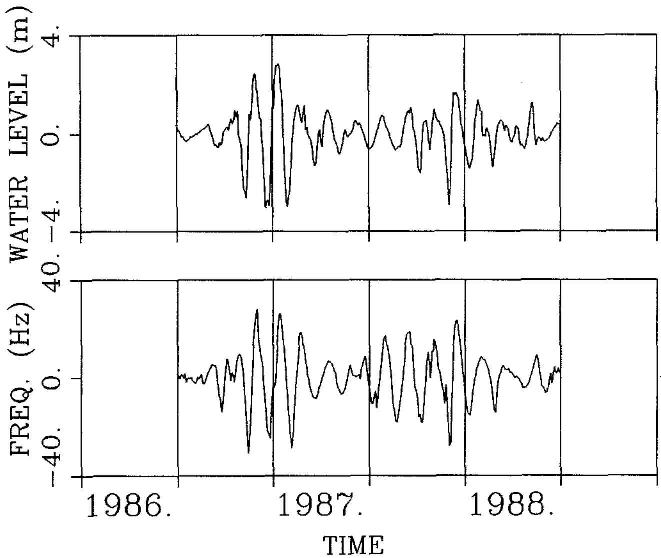

Fig. 8. Filtered water level (top) and deformation (bottom) curves obtained by removing all periods larger than 50 days in the data sets presented in Figs. 5 and 7. The time interval before July 1st 1986 which contains an artificial signal caused by a last calibration of the extensometer was left out of this Fourier analysis

temperature excitation by lowering the extensometer to some 25 or 30 meters. This would not create overwhelming problems for the installation and sealing of the instrument. On the other hand, we do not think it feasible to increase the length of the instrument in order to significantly enhance the sensitivity. Furthermore the verticality of the borehole seems to help avoiding spurious frictions for the wire-disk system.

Acknowledgements

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