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Quartz tube extensometer for observation of Earth tides and local tectonic deformations at the Sopronbánfalva Geodynamic Observatory, Hungary

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Abstract

In May, 1990, a quartz tube extensometer was installed in the Sopronbánfalva Geodynamic Observatory of the Geodetic and Geophysical Research Institute of the Hungarian Academy of Sciences (GGRI) for recording Earth tides and recent tectonic movements. The paper describes the construction of the extensometer and a portable calibrator used for the in situ calibration of the instrument. The extensometer is very sensitive. Its scale factor is 2.093 ± 0.032 nm/mV according to the highly precise calibration method developed at the GGRI. Since the stability of extensometers is strongly influenced by the geological structure and properties of the rocks in the vicinity of the recording site, the observatory instrument system was tested by coherence analysis between theoretical (as the input signal) and measured tidal data series (as the output signal). In the semidiurnal tidal frequency band the coherence is better than 0.95, while in the diurnal band it is about 0.8. Probably this is due to the fact that the noise is higher in the diurnal band (0.4-0.5 nstr) than in the semidiurnal band (0.19-0.22 nstr). Coherence analysis between theoretical and measured data corrected for barometric changes yielded a small improvement of coherence in both frequency bands, while using temperature data correction, no observable improvement was obtained. Results of the tidal analysis also show that the observatory instrument system is suitable for recording very small tectonic movements. The 18 years of continuous data series measured by the extensometer prove the high quality of the extensometer. On the basis of investigations, it was pointed out that further efforts should be done to improve the barometric correction method and that correction for ocean load, as well as considering topographic and cavity effects are necessary to increase the accuracy of determining tidal parameters.

INTRODUCTION

This year is the 20th anniversary of the installation of a quartz tube extensometer in the Sopronbánfalva Geodynamic Observatory (SGO) in a suburb of the City of Sopron, in Hungary. The instrument was built in scientific co-operation between the GGRI and the Institute of Physics of the Earth of the then USSR Academy of Sciences, Moscow, in May, 1990.[1] Since then the instrument has been working continuously except for some interruptions not longer then a few days due to technical problems or maintenance. The instrument is used for observation of the solid Earth's tide[2] and measurement of local tectonic movements and deformations. In both cases the displacements to be measured are very small (in the range of 10^{-9} m). Since the rate of tectonic movements is low (10^{-4} – 10^{-9} m/year), long-term measurements are needed to observe this kind of small displacement. To fulfill these extreme requirements, very sensitive and stable instruments are needed and their sensitivity has to be checked regularly. That is why strenuous efforts were made to solve the calibration of extensometers applied for geodynamic measurements. Since the resolution of rod extensometers is better than 10^{-9} m, the in situ calibration of these instruments represents a real problem. As a first attempt, a calibration apparatus was developed in the GGRI in 1992. This instrument was planned for testing crapoudines[2] and magnetostrictive actuators, which serve as a built-in calibration device for regular daily calibrations of quartz tube extensometers. At the same time this apparatus was also suitable for the in situ calibration of quartz tube extensometers. The high resolution of this device was achieved by two differential condensers, placed at the ends of a rotating arm, which increases the small displacement to be measured. The disadvantage of this calibrator is that the extensometer must be connected to this rotating arm, which causes some problems: instability of the coupling to the extensometer, small, sometimes insufficient place for the calibration apparatus on the extensometer pillar, etc.[3,4,5,6] These disadvantages were eliminated by the development of a new calibration device which does not have moving mechanical parts, e.g. a rotating arm.

In this paper development efforts are described which were devoted to ensure the high reliability of extensometric measurements at the SGO. Beside the construction of the extensometer, the new calibration apparatus is described and the results of the in situ calibration of the extensometer are also given. Since the topography, the quality of the rock in the surroundings of the observation site, the influence of the environmental parameters (temperature, barometric pressure), etc. strongly determine the accuracy of extensometric measurements, the observatory instrument system was also tested. The paper gives the results of tidal and tectonic measurements and demonstrates the high quality of the instrument.

CONSTRUCTION OF THE EXTENSOMETER

The length of the extensometer is 22 m. It is assembled from quartz tubes with a length of 2 m. The diameter of the tubes is 45 mm and their wall thickness is 2.5 mm. Tube pieces are joined together by means of three invar plates with a curved profile. Between the invar plates and the tubes there is a binding material consisting of cement, quartz sand and a two component adhesive. In the course of the installation of the extensometer the plates are gradually pressed together by screws during setting of the binding material for the best filling in the place between plates and tubes (Fig. 1a). This method ensures a firm, very stable tube connection. The jointed tubes are suspended by invar wires on supports (Fig. 1b) which are about 2.5 m apart. The suspending wires have a diameter of 20 μm and they are 25 cm long. This suspension does not obstruct the very small movements of the quartz tube. The screws on the supports serve for leveling of the quartz tube. One end of the extensometer is fixed to the bed rock by means of a stainless steel dowel fixed by concrete in a hole drilled in the bedrock. A magnetostrictive actuator is joined to the other end of the dowel. The jointed quartz tubes are fastened to the other side of the magnetostrictive actuator which can move the quartz tube and serves for the regular daily calibration of the instrument. The displacement of the tube's free end relative to the bedrock is measured by a capacitive sensor. The standing plates of the sensor capacitance are fixed to the bedrock while the moving plate between the standing plates is fixed to the free end of the tube (Fig. 2). The extensometer measures the deformations between its two ends due to different geodynamic phenomena, e.g. Earth's tides, tectonic movements, etc. The longer the tube is, the more sensitive the instrument is according to the relation: $\Delta L = \varepsilon \cdot L$, where ΔL is the displacement between two ends of the tube measured by the capacitive transducer, ε is the strain in the bedrock and L is the length of the extensometer.

The capacitive sensor consists of a differential condenser supplied by a temperature compensated and amplitude stabilized oscillator, which has a frequency of 12 kHz, and its relative amplitude stability is better than 10^{-5}. The output voltage of the capacitive bridge is amplified by an AC amplifier and rectified by a phase-sensitive rectifier. The output voltage of the latter is amplified by a DC amplifier (Fig. 3) and measured by a 24 bit A/D converter (PREMA Digital Multimeter 5017 with multiplexer 5017SC) with a sampling rate of 1 sample/minute. The data are recorded by a computer.

The lower right hand corner of Fig. 4 shows the site of the observatory. The observatory is located on the Hungarian-Austrian border in the eastern foreland of the Alps. Its coordinates are: latitude 47º40’55’’ N; longitude 16º33’32” E; height is 220 m a.s.l. The azimuth of the instrument is 116º. The observatory is an artificial gallery driven into gneiss. The depth of the gallery is about 60 m. Figure 4 shows the ground plan of the observatory and the place of the extensometer in the gallery. The instrument is about 30 m from the entrance of the observatory and it is thermally insulated from the entrance by three doors. At the instrument the yearly and daily temperature variations are less then 0.5 ºC and 0.05 ºC, respectively.

CALIBRATION OF THE EXTENSOMETER

Since the strain changes are very small, the extensometer must have a very high resolution and stability. As small changes in the sensitivity of the extensometer can cause large measuring errors, a regular calibration of the instrument is necessary. For this purpose a magnetostrictive actuator is built into the instrument (Fig. 2) which gives a constant displacement when a constant electric current flows in its coil. The current (150 mA) is switched on for an interval of five minutes every day at a given point of time. The displacement impulse is transferred by the rigid quartz tube to the capacitive transducer and the magnitude of the calibration impulse is recorded. If the magnitude of the impulse is constant, the instrument works properly. By this method, the sensitivity of the capacitive transducer and the digital recording system can be checked. This method also shows if there is any trouble with the tube, (if it is broken, the connection is instable, or the tube is hampered in moving). The magnetostrictive actuator is calibrated by a laser interferometer in a laboratory before installation of the extensometer, and later there is no possibility for its calibration in laboratory. As the parameters of the magnetostrictive actuator can be changed, it also needs a regular calibration. For this reason it is necessary to calibrate the extensometer at least once every year.

The idea of the new calibration method developed in 2006 is very simple. It is a second capacitive sensor which can be regularly calibrated in a laboratory by a laser interferometer while the extensometer can continue working without a break. The difference between the portable and the fixed capacitive sensor is that the standing plates of the portable capacitive transducer are mounted on the free end of a magnetostrictive actuator, as shown in Fig. 5. One end of the magnetostrictive actuator is fixed to a rigid and very stable base plate, which stands on three separate foot screws. The other end of the actuator holds the two outer plates of a capacitive transducer, while its middle plate is fastened to the quartz tube of the extensometer. Thus, the magnetostrictive actuator can move the outer plates of the differential condenser relative to the middle plate and the displacement can be measured by the capacitive transducer. During in situ calibration, the displacement of the free end of the extensometer is simultaneously measured by the portable calibrator and the capacitive sensor of the extensometer. The portable calibrator records both the impulses of the built-in magnetostricive actuator and its own magnetostrictive actuator. Comparing the magnitudes of the two impulses, both the scale factor of the extensometer and the magnitude of the displacement of the built-in magnetostrictive actuator can be determined. By this method, the scale factor of the electronics of the portable calibrator can also be determined. Since the portable calibrator is tested not only in laboratory before and after the in situ calibration, and also during the calibration of the extensometer, a high calibration accuracy can be achieved.

The portable calibrator is also suitable for calibration of extensometers installed without a built-in calibrator. In this case, the comparison of the tidal curves recorded in parallel by the extensometer electronics and by the calibration apparatus can be used for the determination of the scale factor of the instrument.

In order to calibrate the new portable calibration apparatus in a laboratory, it was placed on the stage, and the middle plate of the capacitive transducer was fixed to the stand of a microscope. The displacement of the microscope stage and also the displacement of the outer plates of the differential condenser relative to the middle plate was measured by a HP5508 laser interferometer. The retro reflector prism of the interferometer could be fastened only to the stage of the microscope instead of the magnetostrictive actuator. The calibration apparatus was moved by the micrometer screw of the microscope stage. First, the characteristic curve of the capacitive transducer was determined. The displacement was measured by the laser interferometer and by the capacitive transducer simultaneously. The obtained scale factor of the calibration apparatus is: 1.206 ± 0.002 nm/mV. The actuator was calibrated by the laser interferometer before it was built into the calibrator. Beside the determination of the characteristic curve (displacement vs. current) of the magnetostrictive actuator, the magnitude of a calibration impulse was measured which was obtained by frequently switching a calibration current (155.5 mA) on and off. The average magnitude of the calibration impulse is 859.7 ± 13.7 nm. The portable calibration apparatus and its calibration are described in detail by Mentes.[7]

The scale factor of the Sopronbánfalva extensometer obtained by the new portable calibrator is: 2.093 ± 0.032 nm/mV. The error of the yearly calibrations and the amplitude variations of the daily calibration impulses are within the error range of the scale factor determination.

The frequency-response function of the extensometer was also determined simultaneously by the portable calibrator and the capacitive sensor of the extensometer. During this measurement a sinusoidal current was superposed on a constant DC current to supply the built in magnetostrictive actuator of the extensometer and the output voltage of the extensometer and the portable calibrator were recorded at different frequencies of the sinusoidal current with constant amplitude (Fig. 6).

INVESTIGATION OF THE OBSERVATORY INSTRUMENT SYSTEM

According to Fig. 2, the bedrock between the two ends of the extensometer is also part of the instrument, so the quality of the extensometric measurements depends on the quality of the bedrock in the surroundings of the instrument. Discontinuities in the rock cause a defective function of the instrument. The quality of the observation site was checked by coherence analysis and tidal evaluation of the measured data.

Figure 7 shows the process of tidal measurements. Tidal forces deform the solid Earth and this deformation is measured by extensometers in deep observatories built mainly in the bedrock, where the temperature is stable enough for a highly sensitive instrument. The measured tidal deformation is influenced by cavity and topographic effects and by the movements of the lithosphere plates. Due to the variation of temperature and air pressure, the rock deforms in the surroundings of the observatory (indirect effect), and the variation of these meteorological parameters has also a direct effect on the instrument. This latter can be neglected in the case of the extensometer in the Sopronbánfava Observatory, since the instrument is not sensitive to direct air pressure variations and the temperature is stable in the observatory as it was mentioned above. Coherence analysis was used to test the observatory extensometer system. As input signal, the theoretical tide was always applied which was calculated by the PREDICT program of the ETERNA 3.40 tidal analysis program package.[8] The coherence analysis was repeated by taking the following measured data series as output signal: raw data, data corrected for barometric effect, and data corrected for both air pressure and temperature, where corrections were calculated by linear regression.[9,10] Figure 8 shows the results of coherence analysis. The thin line represents the results using the uncorrected extensometric data as the output signal. In the semidiurnal band, the coherence is better than 0.95, while in the diurnal band it is about 0.8. The thick line shows calculation results when extensometric data was corrected for barometric pressure. The barometric correction resulted in a marked improvement of coherence in both frequency ranges, in contrast with the temperature correction which yielded no change in the coherence function. These latter curves completely coincide in Fig. 8. It means that the observatory instrument system is not sensitive to the diurnal and semidiurnal temperature variations. According to tidal analysis of the data, the noise in the diurnal band (0.4-0.5 nstr.) is about the double of what is obtained in the semidiurnal band (0.19-0.22 nstr.). This may explain the fact that the coherence is smaller in the diurnal band than in the semidiurnal band.

RESULTS OF THE EXTENSOMETRIC MEASUREMENTS

Figure 9 shows the raw extensometric data between 1991 and 2009, in nanostrain (1 nstr=10^{-9}) units (measured displacement/length of the extensometer). The seasonal variations (with yearly period) are caused by the change of the meteorological parameters (indirect effect) and are distinctly visible on the curve. We usually fit a polynomial of the ninth order to the raw data series to get a smoothed curve, which gives the strain caused by tectonic movements if we neglect the drift of the instrument, which can be done according to the stability investigations. The interpretation of the measured strain is discussed in detail by Mentes.[11]
The tidal evaluation of the data was carried out by the ETERNA 3.40 program package. The program calculates the theoretical amplitudes, amplitude factors (measured amplitude/ theoretical amplitude) and the phase leads (the phase shift of the measured wave relative to the theoretical) of tidal strain waves.[7] As an example Table I shows the tidal parameters of the main lunar diurnal O1 and the semidiurnal M2 waves[2] calculated from the data measured in year 2009. The results and their standard variations are in good agreement with the results obtained at other extensometric stations. [12, 13]

Table II shows the amplitude factors of tidal constituents O1 and M2 from yearly data series between 2000 and 2009. The relatively high error of the determination of the amplitude factors may result from the wind load of the rock face of the observatory. This hypothesis was backed up by finite element modeling of atmosphere loading effect for the Sopronbánfalva station carried out at the University of Jena.[14, 15] The thickness of the rock wall between the rock face and the gallery is about 8 m and the extensometer is nearly perpendicular to the rock face (see Fig. 4), so strong westerly wind blasts disturb the instrument, but this has no influence on the long-term tectonic observation.

CONCLUSIONS

Investigations showed that the new portable calibrator has a high accuracy for reliable in situ calibration of extensometers. Its special feature is that it can be also used for calibration of extensometers without a built-in calibrator. Since more extensometers can be calibrated by the same calibrator, a uniform interpretation of the measured data is possible. The results of the yearly repeated in situ calibrations of the Sopronbánfalva extensometer show that the instrument has high stability and accuracy for the reliable determination of tidal parameters and very small, long-period tectonic movements. This is proved also by tidal and coherence analysis.

Extensometric measurements are very sensitive to barometric pressure variations. In addition to the existing methods,[16] new methods should be developed for the barometric correction of extensometric data which also take the regional and global effects[17] into consideration. Measured data should also be corrected for ocean loading, topographic and cavity effects[2] to increase the accuracy of tidal parameters. These latter corrections probably diminish the noise obtained at the tidal evaluation of the data. Beside these corrections, further investigations should be done to reveal the causes of the noise in the diurnal frequency band.

Since the above mentioned effects do not disturb the long-term measurements the extensometer plays a very important role in monitoring of local tectonic deformations.

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Tables

TABLE I. Tidal parameters calculated from the extensometric data measured in 2009

Frequency		Wave	Theor. amplitude	Ampl. factor	Phase lead
from [cpd]	to [cpd]		[nstr]	± stdv.	± stdv. [degree]
0.911391	0.947991	O1	6.5937	0.63±0.05	-12±5
1.914129	1.950419	M2	5.0573	1.16±0.03	-17±2

TABLE II. Amplitude factors calculated from data series measured from 2000 to 2009

Wave	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	Average ± stdv
O1	0.686	0.652	0.687	0.724	0.716	0.695	0.691	0.735	0.692	0.626	0.690 ±0.03
M2	1.087	1.144	1.212	1.186	0.959	1.129	1.292	1.236	1.268	1.163	1.168±0.10

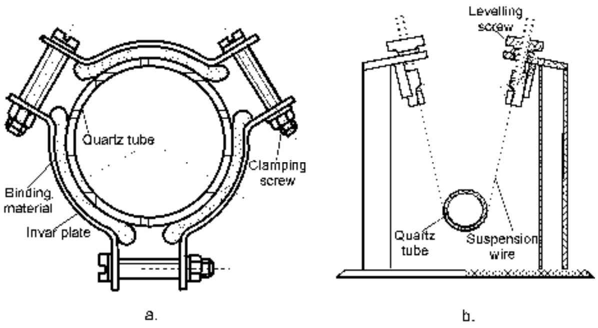

Fig. 1. Joint (a) and suspension (b) of the tube

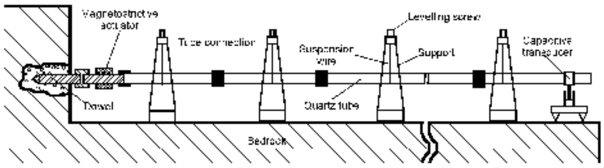

Fig. 2. Construction of the extensometer

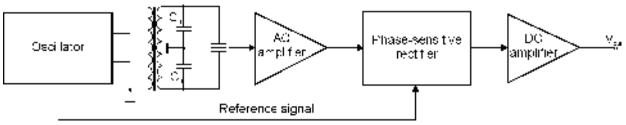

Fig. 3. Block diagram of the capacitive sensor

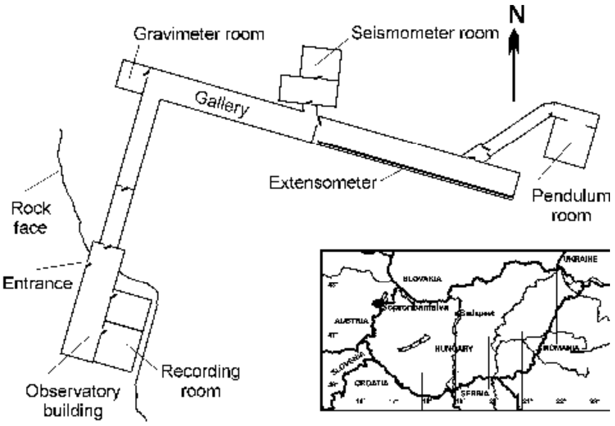

Fig. 4. Ground plan and the site (lower right hand corner) of the Sopronbánfalva Geodynamic Observatory

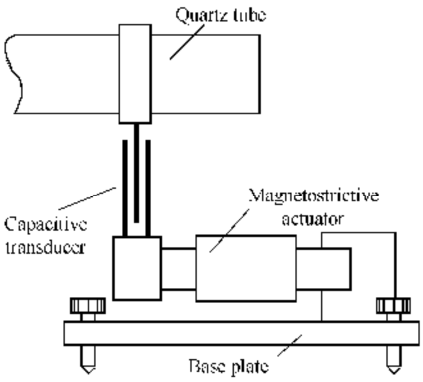

Fig. 5. Principle of the in situ (portable) calibrator apparatus

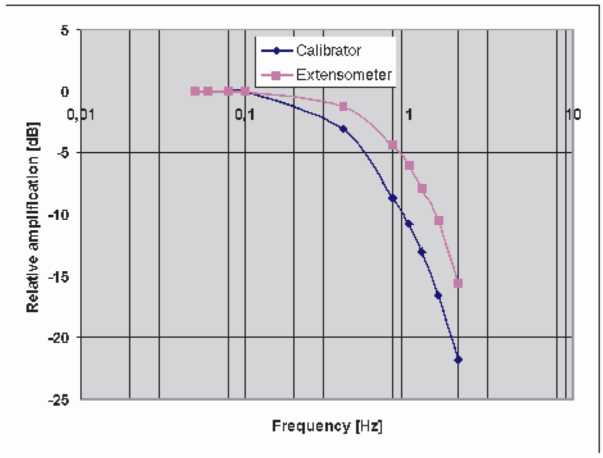

Fig. 6. Frequency-response function of the extensometer

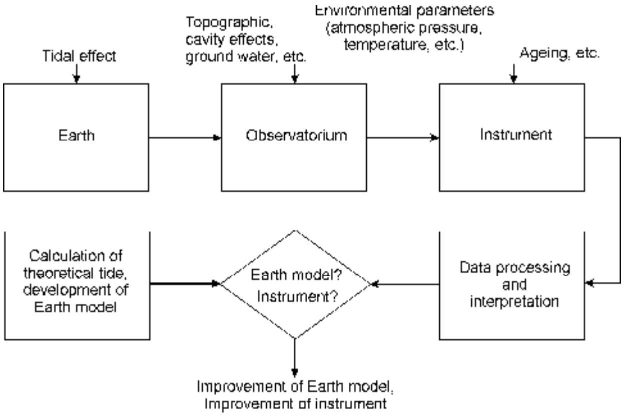

Fig. 7. Block diagram of the tidal evaluation of extensometric data

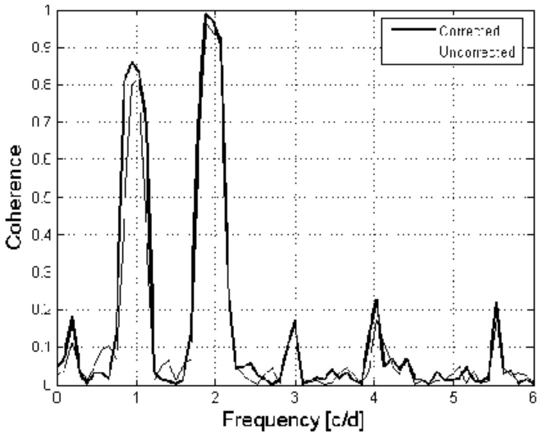

Fig. 8. Results of the coherence analysis

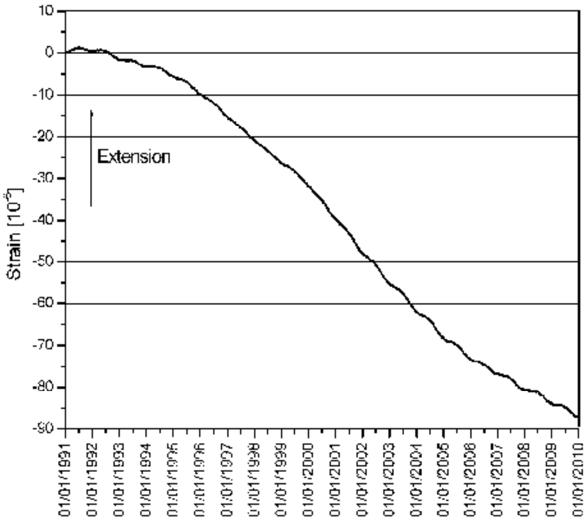

Fig. 9. Strain measured in the Sopronbánfalva Observatory from 01.01.1991 till 31.12.2009.