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A new borehole wire extensometer with high accuracy and stability for observation of local geodynamic processes

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Abstract

Very stable and reliable instruments with high accuracy are required in field measurements for continuous monitoring local geodynamic processes, such as tectonic movements, ground motions in landslide prone areas, etc. A sensitive borehole wire extensometer with low energy consumption was developed in the Geodetic and Geophysical Research Institute of the Hungarian Academy of Sciences to observe very small vertical movements (in the order of a few millimeters) of the upper layer of the soil due to hydrological, meteorological and biological processes. The newly developed instrument eliminates the disadvantages of the borehole wire extensometers which are presently used. Its sensitivity and stability are much higher than these parameters of the previous instruments. The instrument is able to measure distance variations without instrumental drift in a range of 0-4 mm with a resolution of better than 1 μm. Since the effect of the yearly temperature variations can be easily removed from

the extensometric data record, the compensation for the short-periodic (daily) thermal effects on the instrument was of high priority during the design of the instrument.

This paper describes the construction and calibration of the extensometer. The extensometer was installed for monitoring vertical ground movements due to hydro-meteorological processes on the high loess wall of the Danube River at Dunaföldvár, Hungary. The efficiency of the temperature compensation of the instrument was investigated in detail on the basis of the measured data series.

I. INTRODUCTION

In addition to large scale observations of local geodynamic processes, there is a growing need for high precision measurement of very small vertical displacements. This work includes the investigation of the relationships between ground movements and hydrological processes[1-5] (e.g. rainfall, ground water table variations), and the study of soil movements caused by the life processes of the vegetation.[6,7] Research with these aims is very important, especially in landslide prone areas, since these factors strongly influence the stability of the slope.

Extensometers are used to measure changes (ΔL) in a distance (L) between two points of rocks, soils or objects (buildings, bridges, dams, etc.) in geodynamics, engineering geology and geodesy. They are often called strainmeters since the change in distance divided by the distance between the two points (length of the extensometer) gives the relative displacement, called strain: $\varepsilon = \Delta L / L$. The various types of extensometers differ from each other in the method of linking the points between which the distance change is measured and the kind of sensor employed to measure the change. The link can be mechanical (wires, rods and tubes) or a laser beam (fiber optic). In mechanical extensometers, electronic transducers (linear potentiometers, inductive and capacitive transducers, etc.) are used to convert the mechanical displacement into electric signals.

At present, the fiber optic strain sensors are widely used for continuous measurements of displacement and deformation in engineering geodesy[8] and their use is also spreading in landslide monitoring[9] since they are not sensitive to environmental effects. Until now the electronics of these sensors have been complicated and expensive and their energy consumption is too high to use them without supervision far from electric mains. For this reason invar wire extensometers are generally used for landslide observations. Corominas et al.[10] used an invar wire extensometer with a potentiometer as a displacement sensor. However, the potentiometer has contact problems under rough environmental conditions and it is not reliable in continuous long-term field measurements. In this type of extensometer, a mechanical amplification, e.g. a balance arm[11] is used to increase the sensitivity of the instrument but the moving mechanical part can increase the instability of the extensometer. The dew formed during low night temperatures causes mechanical and electronic problems in closed boreholes. The dust carried by different insects, e.g. ants, into the box of the electronics at the top of the borehole causes a lot of problems in moving mechanical parts. To eliminate these problems, a reliable, high sensitive invar wire borehole extensometer without moving precision mechanical parts, with very simple electronics and very low energy consumption was developed in the Geodetic and Geophysical Research Institute of the Hungarian Academy of Sciences (GGRI). This paper describes the construction and the calibration of the extensometer and the effect of the temperature on the instrument is investigated in detail on the basis of measured data series.

II. CONSTRUCTION OF THE EXTENSOMETER

Extensometers measure the change of distance between their two endpoints. In wire extensometers, one end of the wire is fixed to one end of the distance to be measured; the other end can move freely. This movement relative to the other end is measured by an electronic transducer which transforms the displacement of the free end of the wire into an electric signal. In wire extensometers invar wire is used due to its very low coefficient of thermal expansion. Figure 1 shows the construction of the instrument. One end of the invar wire is anchored to the bottom of the borehole by a concrete mass which is fixed to the borehole by concrete during the installation. This part of the borehole is not encased with PVC tube so that there will be a stable connection of the lower end of the wire to the ground at the bottom of the borehole. At the upper end of the borehole, (which is about half a meter below the surface), there is a concrete block around it which ensures a good connection to the ground. This concrete block holds a steel frame with a pulley which can revolve around its axle fixed to the frame. The invar wire is placed around the pulley and it is held tight by an iron counterweight. The vertical motions of the ground between the ends of the borehole cause the displacement of the iron counterweight. Its position is measured by a proximity inductive distance sensor produced by the firm BALLUFF[11]. A closed housing contains the sensory element and associated electronics in a single package, so it is not sensitive to humidity and dust. The working range of the sensor is 1-5 mm. The nearest position of the sensor relative to the iron weight has to be 1 mm according to the data sheet of the sensor. Therefore, the sensor is installed in about 3 mm away from the iron counterweight when it is at rest. In this case the movement of the counterweight can be measured in the range of ± 2 mm relative to its resting position. This solution provides a contactless measurement. The sensor needs a power supply of between 15 and 30 V and its output voltage is in the range of 0-10 V. The data is collected by a data logger at a rate of 1 sample/hour. The batteries and the data logger are placed in a thermally insulated steel box dug into the ground. This box also closes the borehole.

The main parts of the instrument are the inductive distance sensor and the iron counterweight stretching the invar wire. The counterweight weighs 4 kg to ensure a reliable turn of the pulley and so a constant tension on the invar wire. The diameter of the invar wire is 0.8 mm.

The stress in the wire is 0.8 MPa which is much less than the elastic limit given for invar (240 MPa). Consequently, the continuous elongation of the invar wire can be disregarded since the magnitude of the measured displacement due to a given strain change is in direct proportion to the length of the extensometer. The maximum length of the invar wire should be determined by considering the highest possible displacement to be expected at the location of the instrument. In this maximum range (±2 mm) the length of the wire can be adjusted according to the thickness of the soil layer in which the deformation will be measured.

The operation of the inductive distance sensors is based on the interaction between a metallic conductor and an alternating magnetic field. The sensor consists of a core wound with a coil which is fed by a high-frequency signal from an oscillator. The coil generates a magnetic field surrounding the coil and produces eddy currents in the nearby conducting material, thus removing energy from the field and reducing the amplitude of the signal of the oscillator. The closer the conducting material is to the object, the greater the absorbed power will be. It follows from this principle that nearby conducting materials and outer magnetic fields can disturb the work of the sensor. For this reason, the diameter of the counterweight (100 mm) was chosen to be much greater than the diameter of the sensor (18 mm).Thus, the counterweight also serves as a magnetic shield.

III. CALIBRATION OF THE SENSOR

Instead of the standard plate produced by the firm BALLUFF for their inductive distance sensors,[12] we use the iron counterweight as the moving target in our extensometer. According to our investigations the sensitivity of the sensor depends on the dimension, shape and material of the target whose displacement has to be measured. Thus the inductive distance sensor was calibrated together with the iron counterweight of the extensometer used as a counterpart of the inductive distance sensor. During the calibration process, the iron counterweight was immovable and the inductive distance sensor was fixed to the stage of a microscope and moved against the counterweight by the micrometer screw of the microscope. The displacement of the inductive distance sensor was measured by means of an HP 5508 laser interferometer. Figure 2 shows a series of the measurements and the regression line fitted to it. The Figure demonstrates the non-linearity of the sensor. The steepness of the regression line gives the average sensitivity or in other words the average scale factor of the sensor which is 2.570±0.004 V/mm obtained from repeated measurements. The calculated linearity error of the sensor is less than ±120 μm which is the same value as given by the manufacturer. Since the linearity error of the sensor is high, the scale factor can only be used for planning measurements to estimate the output voltage range due to movements to be expected. For determination of the displacement from the output voltage the non-linear characteristic of the sensor has to be used. To determine this characteristic, a 3rd order polynomial was fitted on the values obtained from three back and forth measurement series:

$$y = 4.40553 - 5.45681 \cdot 10^{-4} \cdot x + 4.27880 \cdot 10^{-8} \cdot x^2 - 2.84527 \cdot 10^{-12} \cdot x^3, \qquad (1)$$

where x is the output voltage of the sensor in mV and y is the distance in mm. The coefficient of the determination of the equation is: $R^2 = 0.99994$. The standard deviation of the differences between the polynomial and the measured values (residuals) is 2.4 μm. The residual curve (a polynomial fitted to the residuals) can be used for correction of the measured data to achieve a submicrometer accuracy.

IV. COMPENSATION OF THE TEMPERATURE EFFECT

The direct effect of the temperature changes both the dimension of the iron frame and the length of the invar wire. Figure 3 shows the frame with the pulley, the counterweight and the sensor and their dimensions. Due to the thermal expansion of the concrete block and the section of the iron frame between the concrete block and the upper edge of the transverse beam (section l_2), the sensor and the counterweight move in the same direction and therefore their distance does not change. Thus, the expansion of the l_2 section and the concrete block do not cause measurement error. Due to the thermal expansion of the l_1 section of the frame and the radius of the pulley, the counterweight moves up and down due to the thermal expansion and contraction of the invar wire. Consequently, the effect of the temperature can be compensated by changing the length of the l_1 section of the frame. Since the counterweight and the sensor are also made of iron, the change of the distance between the sensor and counterweight due to 1 °C temperature change can be calculated as follows:

$$\Delta d = [(l_1 + r) - (l_3 + s)] \cdot \alpha_{ir} = [140 + 30) - (90 + 10)] \cdot 1.17 \cdot 10^{-5} = 81.9 \cdot 10^{-5}\ mm/°C, \qquad (2)$$

where α_{ir}=1.17·10^{-5} 1/°C, which is the coefficient of the thermal expansion (CTE) of the iron. If we assume, that the temperature of the upper section of the invar wire (700 mm) above the frost-line (at a depth of 80 cm from the surface) is equal with the surface temperature and the thermal expansion of the invar wire below the frost-line can be disregarded then the thermal expansion of the invar wire caused by 1 °C can be estimated:

$$\Delta l = l \cdot \alpha_{in} = 700 \cdot 1.2 \cdot 10^{-6} = 84 \cdot 10^{-5}\ mm/°C, \qquad (3)$$

where α_{in}=1.2·10^{-6} 1/°C, the CTE of the invar.

The measurement error due to 1 °C temperature change is:

$$e = \Delta l - \Delta d = 84 \cdot 10^{-5} - 81.9 \cdot 10^{-5} = 2.1 \cdot 10^{-5}\ mm/°C \cong 0.021\ \mu m/°C. \qquad (4)$$

The long periodic temperature variation at the bottom of the borehole is less than 8 °C, while the short periodic (daily) variation is less than 0.2 °C. It means that only the effect of the daily temperature variations can be compensated on the basis of the above mentioned assumptions. The long-term temperature effect (e.g. in case of the observation of tectonic movements) can be much more easily corrected mathematically than the short-periodic (daily) effects. The frame of the instrument was designed according to the assumptions mentioned above. The adjustable position of the transverse beam (changing the l_1 section) makes it possible to achieve an optimal thermal compensation.

V. INVESTIGATION OF THE TEMPERATURE EFFECT

The instrument is used to observe for vertical movements on the high loess wall along the River Danube in Dunaföldvár, Hungary. A detailed description of the test site is given by Mentes et al.[13] The vertical extensometer was installed close (1.5 m) to a highly sensitive borehole tiltmeter (Applied Geomechanics Inc. 722A) on the top of the loess wall in June, 2005. The construction of the borehole is shown in Fig. 1. The invar wire is 2.5 m long for observations of small vertical movements of the upper layer of the loess wall due to the pore pressure variations of the soil which are caused by precipitation, temperature, ground water variations and vital processes of the vegetation. The analogous output voltage of the extensometer was digitized and recorded by the data logger of the borehole tiltmeter (Scientific Campbell XR 10). The borehole temperature was measured by the built-in temperature sensor of the tiltmeter at the bottom of the borehole. The surface temperature was measured by a thermocouple connected to the datalogger in the steel chest containing the batteries and the datalogger of the tiltmeter. This can be done since the construction of the two boreholes is the same and they are very close to each other. All data were sampled hourly and were downloaded from the data logger at about 50 day intervals.

The extensometric, surface and borehole temperature data series from August 1, 2007 to February 29, 2008 were chosen for the investigation of the effect of temperature. Figure 4 shows the raw data. The correlation coefficient between the surface and borehole temperature is 0.727 (R^2=0.5286); between the surface temperature and extensometric data it is 0.517 (R^2=0.2668) and between the borehole temperature and extensometric data it is 0.888 (R^2=0.7891). This latter correlation is obvious in Fig. 4. This good correlation is due to the thermal expansion of the soil and due to the fact that the vertical extensometer is not exactly corrected for the long-term thermal effects. In geodynamics long-term observations (over a few years) are needed to determine the small movements. The long-term thermal effects can be easily corrected by a simple linear regression method.

In contrast with the surface temperature, the borehole temperature has no high frequency components and it has a phase lag to the surface temperature. The temperature of the invar wire is equal with the borehole temperature and the thermal expansion of the frame is synchronous with the surface temperature. For this reason the long-term thermal compensation of the instrument is impossible.

To examine the daily thermal effects, the trend and long-periodic variations were removed by high-pass filtering the data series with a cut-off frequency of 0.01 cycle/day. The filtered data series are plotted in Fig. 5. The correlation coefficient between the filtered surface temperature and borehole temperature is -0.063 (R^2=0.0004) and between the filtered borehole temperature and extensometric data is 0.283 (R^2=0.0804). The correlation coefficients indicate that the temperature compensation of the instrument is good in the short-periodic range. Figure 6 shows the data in the period from September 1, 2007 to September 29, 2007 to present the lack of correlation between the extensometric and temperature data. In Figs. 5 and 6 the variations of the extensometric and temperature data are in a plus-minus range relative to the long-periodic variations removed by the high-pass filter. In Fig. 4 shows that the long-periodic surface temperature variation from August 1, 2007 to February 29, 2008 is 40 °C (from -15 to +25 °C); the borehole temperature variation is 8 °C (from 12 to 20 °C). The short periodic surface temperature variation is in the range of 20 °C, while the short periodic borehole temperature variation is less than 0.8 °C (Fig. 5), which proves that the assumptions made during the design of the temperature compensation of the instrument were right.

The investigation of the long-term temperature corrected extensometric record between September 1, 2005 and December 31, 2010 proved that the instrument does not have a remarkable drift which can be attributed to the elongation of the invar wire due to the tension of the counterweight and due to the temporal changes of the parameters of the inductive sensor.

Figure 7 shows the surface (SFT) and borehole (BHT) temperatures, the extensomeric data and the north (N-tilt) and east (E-tilt) tilt components recorded by the two component borehole tiltmeter installed near the vertical extensometer in a five day interval from June 5, 2009 to June 10, 2009. The exponential rising and falling edge of the surface temperature is caused by the warming up and cooling down of the steel chest where the surface temperature is measured. The borehole temperature is measured in the tiltmeter which is fixed to the ground by stamped quartz sand so it operates under sand and is not sensitive to the surface temperatures. The change of the ground temperature is less than 0.3 °C. The resolution of the temperature sensor is 0.1 °C and this causes the jagged temperature curve. The vertical extensometer data record shows a curve of daily period with exponentially rising and falling edges similarly to the north and east tilt components. Similar curves were obtained during a pump test when the water was periodically pumped from a well and ground tilts were measured in the vicinity of the well by borehole tiltmeters.[14,15] We can assume that the measured movements are caused by the pore pressure variations of the ground due to the water content variation of the soil which is in connection with the evapotranspiration[16-18] and so with the surface temperature of the test area. This parallel record also proves that the vertical extensometer is suitable for reliable measurement of small ground movements and it is not sensitive to the direct effect of the temperature.

V. CONCLUSIONS

The new borehole wire extensometer is a very simple sensitive and stable instrument without mechanical amplification or any other moving mechanical parts connecting the invar wire to the displacement transducer. Due to the new solution of the displacement transducer and the effective thermal compensation this new extensometer is not sensitive to the variation of environmental parameters (e.g. temperature, air pressure, etc.) and it does not have a detectable instrumental drift. It practically needs no maintenance with the exception of changing batteries and downloading data at intervals of 50-60 days.

The newly developed instrument eliminates the disadvantages of the presently used borehole wire extensometers. Its sensitivity and stability are much higher than those of the previous instruments. The sensitivity and stability of the new borehole wire extensometer are about the same that of the fiber optic extensometers while the energy consumption of the new extensometer is much lower than the fiber optic extensometers.

The measurements on the high loess wall showed that the instrument is suitable to measure small distance variations caused by meteorological and hydrological processes, and even distance variations due to the evapotranspiration, with a resolution in the order of 0.1 μm.

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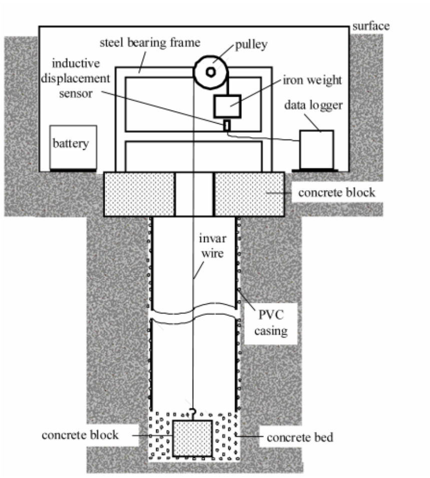

Fig. 1. Sketch of the borehole wire extensometer

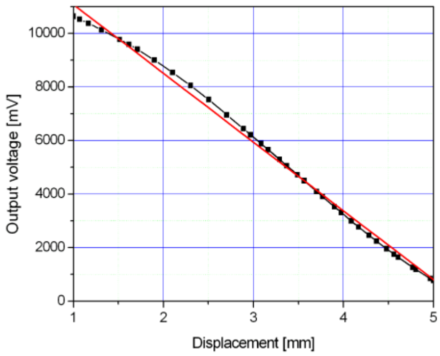

Fig. 2. Characteristic of the BALLUFF inductive distance sensor with the fitted regression line

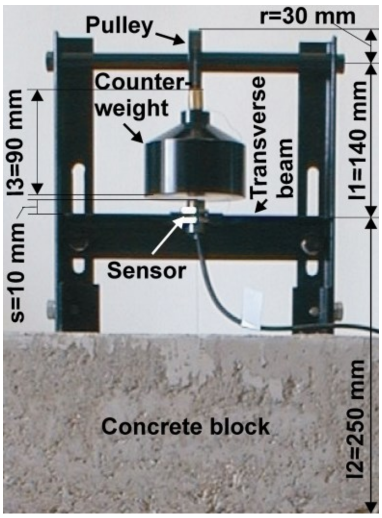

Fig. 3. The iron frame and the concrete block of the vertical extensometer

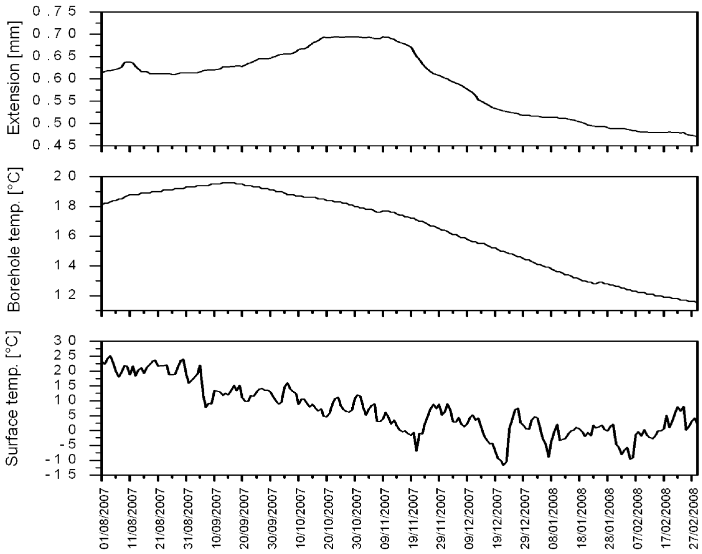

Fig. 4. Extensometric, surface temperature (measured at the top of the borehole in the steel box) and borehole temperature (measured at the bottom of the borehole) data recorded from August 1, 2007 to February 29, 2008

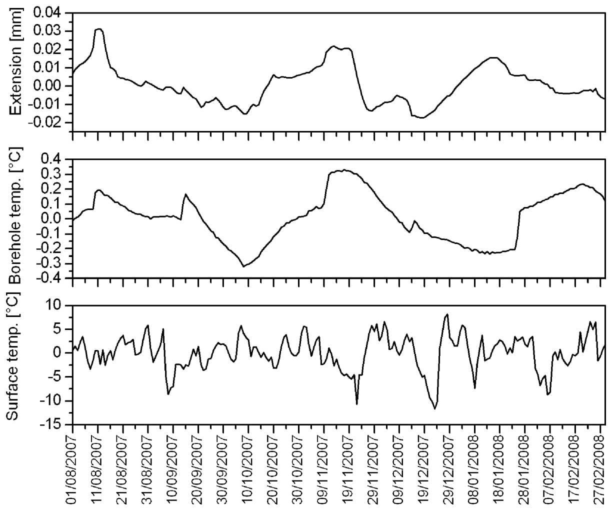

Fig. 5. Variations of the high-pass filtered (cut-off frequency: 0.01 cycle/day) extensometric, surface (measured at the top of the borehole in the steel box) and borehole temperature (measured at the bottom of the borehole) data from August 1, 2007 to February 29, 2008

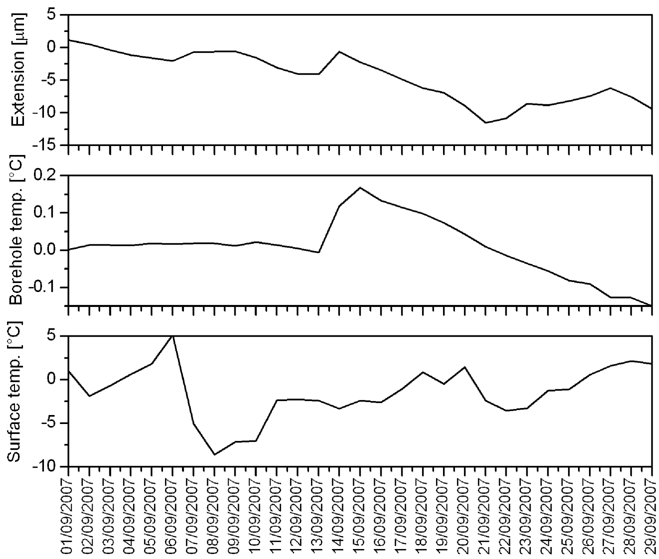

Fig. 6. Variations of the high-pass filtered (cut-off frequency: 0.01 cycle/day) extensometric, surface temperature (measured at the top of the borehole in the steel box) and borehole temperature (measured at the bottom of the borehole) data from September 1, 2007 to September 29, 2007

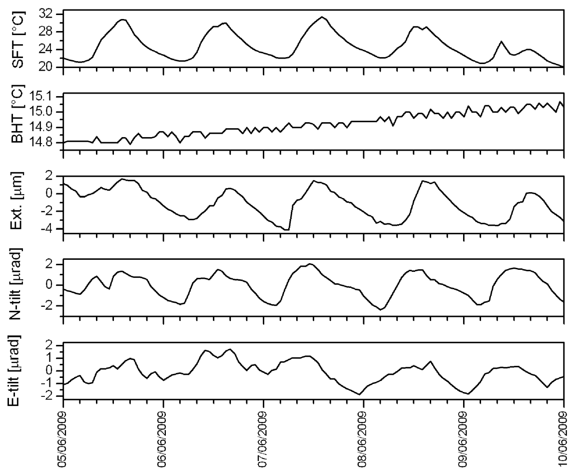

Fig. 7. Comparison of tiltmeter and vertical extensometer data in the period from June 5, 2009 to June 10, 2009. SFT and BHT are the surface and borehole temperature, respectively. Ext. is the data measured by the vertical extensometer. N-tilt and E-tilt are the north and east tilt components recorded by the two component borehole tiltmeter.